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RELATIONS OF BAUXITE AND KAOLIN IN THE ARKANSAS BAUXITE DEPOSITS.[1]

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ABSTRACT.

Investigation of the Arkansas bauxite deposits by the U. S. Geological Survey during the years 1942 to 1945 has brought out the fact that secondary kaolinization or silication of the bauxite is much more common than has been generally recognized. On the other hand no direct evidence was found of the development of bauxite from kaolin. These facts have led us to reconsider the genetic relations of bauxite and kaolin.

We do not mean to deny that there has been direct kaolinization of the nepheline syenite; but in view of the above observations and of the character of the kaolin derived from bauxite, we believe that the relations of bauxite and kaolin in the Arkansas deposits are more readily explained on the assumption that the bauxite is derived directly from the nepheline syenite, rather than from kaolinized nepheline syenite. The silica causing its subsequent kaolinization may be derived from overlying sediments or from remnants of unbauxitized nepheline syenite within or adjacent to it.

Our conclusions about the relations of the kaolinized and bauxitized nepheline syenite are based entirely on rock weathered in place.

KAOLINIZATION OF BAUXITE.

KAOLINIZATION penetrates bauxitic rock in various ways. One type of kaolinization begins along irregular braiding veins that may be on a large or on a small scale. These veins first cut the bauxite into irregular bodies that fit each other quite closely. Such veins on a large scale are illustrated in Fig. 1. As these veins widen by kaolinization of the surrounding rock the surviving bodies of the original bauxitic rock may become rounded to form a pseudo-conglomerate in a kaolinitic clay matrix, or they may retain their angular outlines and form bauxitic pseudo-fragments in a kaolinitic clay. Fig. 2 illustrates such pseudo-fragmentation on a small scale and shows the development, by chemical alteration, of a clay in which scattered remnants of the original rock appear like mechanical fragments in transported material. In the lower left corner of Fig. 2 a body of the original clay is penetrated, with-

[1] Published with the permission of the Director of the Geological Survey, U. S. Department of the Interior.

out disruption, by fine veinlets of an alteration product. As these veinlets widen, remnants of the original rock become widely separated in the alteration product as in the upper part of Fig. 2. Some remnants are themselves penetrated by a mesh of fine veinlets of the alteration product.

The same process, with the original rock bauxite, and the invading material kaolinitic, has been observed; but no specimen illustrating the early stages is available at the present time. The product of the process in bauxitic rock, pseudo-fragments of bauxite in kaolin in relations that leave no room for doubt that they were formed by that process, are illustrated in Fig. 5. Finally kaolinization may involve the entire rock leaving little or no megascopic evidence of relict structures.

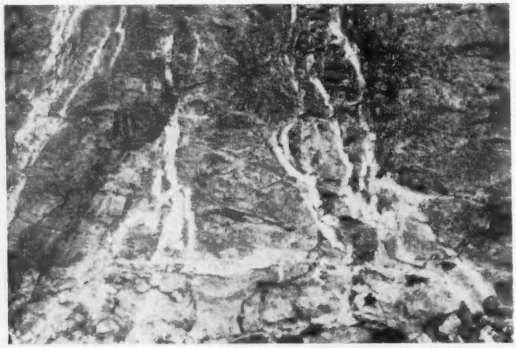

FIG. 1. Irregular braiding veins of kaolin penetrating bauxitized nepheline syenite in the Norton mine, T. 2 S., R. 14 W., Saline County, Arkansas. The veins apparently penetrated the bauxite from below and die out upwards. The collecting bag on the left gives the scale.

Such veining may cut any pisolitic or "granitic" [2] bauxite, but is generally best developed in "granitic" bauxite at the bottom of the bauxite section, close to underlying kaolinized nepheline syenite.

Sometimes kaolinization takes place along broader, sharply defined veins cutting through good "granitic" bauxite (Fig. 3). The pattern of the veins illustrated in Fig. 3 suggests that they formed along joints in the bauxite that were relict from joints in the nepheline syenite from which the bauxite was derived. Many of these veins are as much as 4 inches to 6 inches wide. As can be seen in Fig. 3 these veins also widen in places and replace the wall rock.

Another type of kaolinization advances into the bauxitic rock quite irregularly (Fig. 4).

In detail the kaolin of any of these three large-scale types may show a pseudo-fragmental structure (Fig. 5) indicating that within the larger struc-

[2] The term "granitic" is applied, in the Arkansas fields, to bauxite in which the characters of the nepheline syenite from which it was formed, especially the shape of the feldspars, are more or less well preserved.

ture kaolin started to form along many small irregular fissures as in the specimen of Fig. 2.

Veins of kaolinitic clay forming a small-scale mesh in bauxite are more characteristic of the top of the bauxite section in pisolitic rock than of other parts of bauxite bodies, and in good examples cut through hard, well developed pisolites and matrix alike (Fig. 6).

FIG. 2. Pseudo-fragmentation in kaolinitic rock. Sawed face of core specimen AB–262 from a depth of 412 feet in NE¼ SW¼ sec. 36, T. 2 S., R. 14 W., Saline County, Arkansas. Approximately natural size. Parts of a white kaolinitic clay (light areas) have been altered to a slightly pinkish gray kaolinitic clay (darker areas) with small siderite pellets, a rather common alteration in the Arkansas bauxite deposits.

We said above that the kaolinization that accompanies pseudo-fragmentation may leave little or no megascopic evidence of the original structure of the rock. In thin section under the microscope, however, vague relict structures such as pisolites, feldspars, irregular true fragments, and so on, can in many instances be recognized.

Sometimes kaolinization permeates bauxitic rock without effacing its structures. Such kaolinization may be difficult to recognize megascopically, but microscopic examination shows kaolinite as the major constituent about the bauxite mineral gibbsite, with well developed bauxitic structures such as pisolites or relict gibbsitized feldspars more or less replaced by kaolinite.

Although this diffuse type of kaolinization may not be distinguished as such by the unaided eye it results in a whitening of the entire rock and a weakening of the contrast between constituents such as pisolites and matrix.

Therefore, once it has been recognized microscopically it can be surmised from the general appearance of the rock affected by it.

RELATION OF BAUXITE TO KAOLINIZED NEPHELINE SYENITE.

In the preceding section we discussed the evidence for kaolinization of bauxite and pointed out that it may often leave few traces of the original bauxitic rock. We now wish to consider the relation of the bauxitized nepheline syenite to the kaolinized nepheline syenite.

FIG. 3. Kaolinitic veins replacing "granitic" bauxite along straight fissures. African Camp Mine of the Alcoa Mining Co., sec. 15, T. 2 S., R. 15 W., Saline County, Arkansas. The hammer near the center gives the scale.

We follow prevailing opinion in regarding the "syenitic clay"—that is to say, white kaolinitic rock showing distinctly the structure of the nepheline syenite—as formed directly from the nepheline syenite, not by kaolinization of bauxitized nepheline syenite. Since bauxitized nepheline syenite is generally loose and friable in structure, whereas "syenitic clay," which we prefer to call kaolinized nepheline syenite, is much denser and represents the original constituents of the nepheline syenite more completely, it does not seem possible that the kaolinized nepheline syenite could have been derived from the bauxitized nepheline syenite.

But we question the prevailing belief that the Arkansas bauxite was formed by bauxitization of kaolin or kaolinized nepheline syenite.

The arguments for the development of bauxite from kaolin, generally accepted since the work of Mead[3] are: 1) the invariable occurrence of kaolin between bauxite and syenite; 2) the lithologic and chemical upward gradation

[3] Mead, W. J., Occurrence and origin of the bauxite deposits of Arkansas. ECON. GEOL., vol. 10, pp. 28–54, 1915.

in many places from fresh nepheline syenite through kaolinized nepheline syenite to bauxitic clay and bauxitized nepheline syenite; 3) the presence of residual cores of nepheline syenite surrounded by kaolinized nepheline syenite completely enveloped by bauxitized nepheline syenite.

This interpretation seems also to be supported by the observation that in places large "rootlike" masses of "granitic" bauxite extend down into the underlying kaolinitic clay, suggesting that the bauxite is working down into the kaolin.

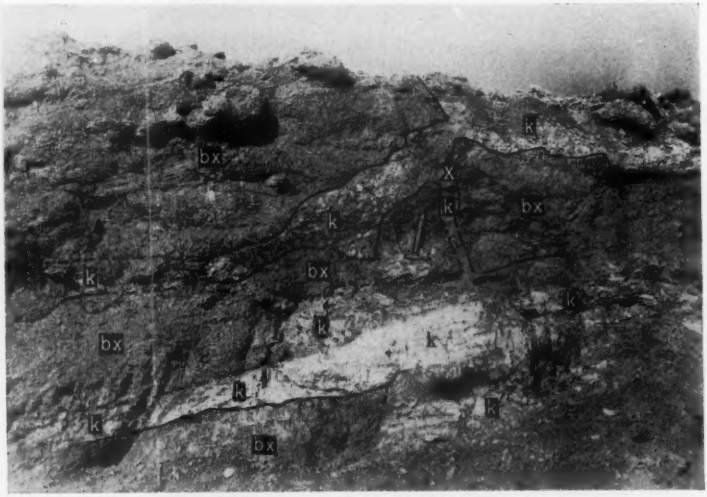

FIG. 4. Irregular kaolinization of bauxitized nepheline syenite at the north edge of the Pruden Pit of the Alcoa Mining Co. just southwest of the town of Bauxite. (Bauxitized nepheline syenite lettered bx; kaolinized areas lettered k.) Kaolinization has apparently proceeded downward from the present surface of the bauxite body. Some of the kaolinitic clay has a pseudo-fragmental structure as is illustrated in Fig. 5, which represents a specimen taken at the location marked X in this figure, at the upper end of the vertical vein. The contacts between bauxite and kaolinitic clay in this exposure are in general quite sharp. The hammer gives the scale.

However, we have nowhere seen bauxitized nepheline syenite grading into kaolinized nepheline syenite. The sequence from kaolinized nepheline syenite with more or less open texture to bauxitized nepheline syenite is marked, wherever we have seen it, by an intermediate zone of compact kaolinitic clay, massive or with a pseudo-fragmental structure, but lacking an open granitic texture. Mead recognized this dense clay but attributed it to "slumping or packing of the kaolinized rock."[4] What he describes seems to correspond rather closely to what we illustrate in Fig. 4. Mead describes this clay as

[4] Idem., p. 51.

"extending *to* the surface" [italics are ours]. The kaolinitic clay illustrated in Fig. 4 seems evidently to have worked *down from* the surface along zones of weakness. Formation of this clay by silication downward from the surface

FIG. 5. Specimen from the point marked X in Fig. 4, showing a kaolinitic vein in contact with bauxitized nepheline syenite. The bauxitized nepheline syenite on the right when fresh was very crumbly, and mottled brown and green. A year later it is yellowish white and red. The dark pseudo-fragments in the vein are remnants of bauxitized nepheline syenite. They are red, and were, we believe, that color when the specimen was collected. The kaolinitic matrix is tough and light colored. The form of the kaolinitic parts of the exposure, as shown in Fig. 4, make it obvious that the kaolin of this specimen has replaced the bauxitized nepheline syenite leaving the dark bauxitic bodies as pseudo-fragments. Natural size.

also explains Mead's observation of "masses of unaltered clay" [silicated bauxite] "at the surface of the bauxite." We also have seen such clay surrounding residual "boulders of decomposition" as illustrated in Fig. 7. But there was no distortion there such as Mead mentions.

The relations of this dense clay to overlying and surrounding bauxite are of kaolin attacking bauxite, as shown by veins of the clay penetrating the bauxite, and by remnants of bauxite surrounded and penetrated by the clay. Because of this, and because the clay has no granitic texture, it could not have altered to the adjacent bauxitized nepheline syenite. We believe that, on the contrary, it is later than bauxitization.

If that interpretation is accepted it might be claimed that this compact clay covers up a transition that originally existed between the kaolinized and

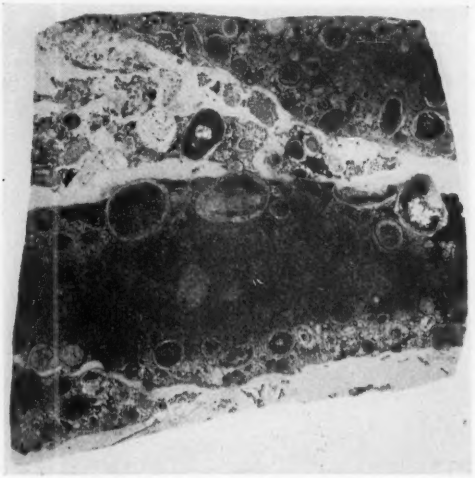

FIG. 6. Veins of kaolinitic clay in hard pisolitic rock. Core specimen 612–1 from a drill hole in sec. 28, T. 2 S., R. 14 W. Saline County, Arkansas. The pisolitic rock is various shades of brown. The specimen illustrates well the range of phenomena involved in kaolinization. The light zone adjacent to the kaolin veins, especially well developed along the bottom vein, is presumably diffusely kaolinized. The alteration of pisolites from stages in which they are merely cut by veins to stages in which they appear merely as vague kaolinized outlines can be seen. In parts of the kaolinitic veins minute pseudo-fragments or clusters of pseudo-fragments survive. Natural size.

bauxitized nepheline syenite. Until the problem is given further study the possibility of such a coincidence must be recognized. It seems improbable, however, if there was a zone between bauxitized and kaolinized nepheline syenite in which bauxitization took place, that such a zone would so generally have been completely concealed by later kaolinization.

Much evidence is accumulating to support the belief that at least under certain conditions gibbsite precedes kaolin in the weathering of all but the most silicic igneous rocks. That was Harrison's [5] observation in British Guiana.

[5] Harrison, J. B., Katamorphism of igneous rocks under humid tropical conditions. Imper. Bur. Soil Sci., Rothamsted Exper. Sta., Harpenden, England, 79 pp. [1933?].

Studies of soils of the United States by Alexander and his colleagues [6] led to this same conclusion. In neither of the publications cited are the weathering products of nepheline syenite discussed. Alexander and his colleagues state that "the impression is held" [by them, probably] "that plagioclase feldspars approaching albite in composition have less tendency than the highly calcic ones to give gibbsite upon weathering." [7] Nevertheless, it seems probable that,

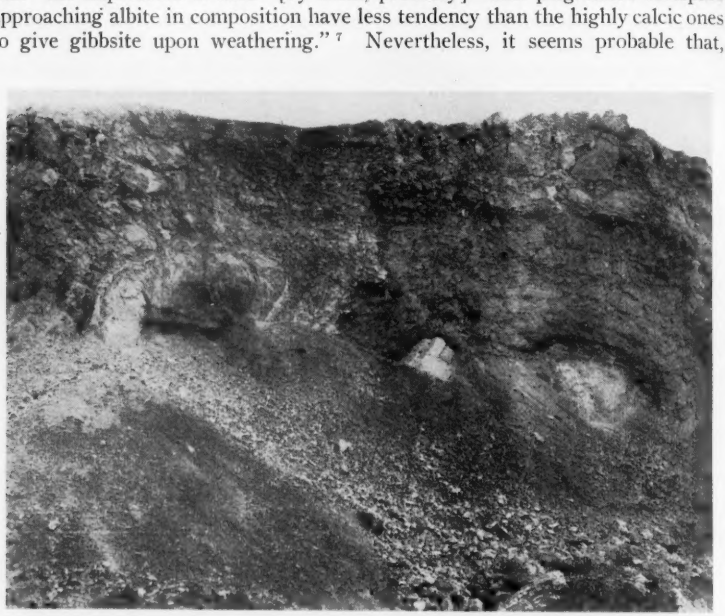

FIG. 7. Residual, more or less spherical masses ("boulders") of weathered nepheline syenite (white) in the midst of nepheline syenite bauxtized in place. Same general locality as Fig. 4, but opposite side of the road cut through the bauxitized nepheline syenite and 200 to 300 feet or so farther down slope and away from fresh nepheline syenite. The white partly kaolinized nepheline syenite is separated from the surrounding bauxite with granitic texture by a rather sharply defined layer, 6 inches to a foot thick, of a dense ocherous kaolinitic clay. Adjacent parts of the matrix of "granitic" bauxite have been partly kaolinized to a pseudo-fragmental clay consisting of remnants of bauxite in kaolinitic clay. The height of the face from the bottom of the exposure of the right hand kaolinitic "boulder" to the top is 19 feet.

under the conditions that produce bauxite, nepheline syenite weathers more like basic than like silicic rocks.

Clarence S. Ross of the U. S. Geological Survey has found that a rock from British Guiana, locally called dolerite, like nepheline syenite a sub-silicic rock, has altered directly to well crystallized gibbsite.

[6] Alexander, L. T., Hendricks, S. B., and Faust, G. T., Occurrence of gibbsite in some soil-forming materials. Soil Sci. Soc. Amer. Proc., vol. 6, pp. 52–57, 1941.

[7] Idem., p. 56, column 2.

Evidence in support of the assumption that nepheline syenite weathers directly to gibbsite is afforded by the "granitic" bauxite of Poços de Caldas, Brazil, which, according to Teixeira,[8] rests directly on the nepheline syenite from which it is derived.

Clarke[9] in 1924 questioned the possibility of the transformation of kaolinitic clay to bauxite. On the other hand Harrison[10] believes that clays consisting of hydrated aluminum silicates (what he calls pot clays) can be desilicated to bauxite.

In view of the conflicting evidence from these and other sources about the derivation of bauxite from kaolin; the abundant evidence, in the Arkansas field, of kaolinization of bauxite; and the absence there, to the best of our knowledge, of any observation of the bauxitization of kaolinized syenite, we believe that the assumption that kaolinization of the nepheline syenite is an intermediate step in its weathering to bauxite should be questioned.

U. S. Geological Survey,
Washinton, D. C.,
May 9, 1946.

[8] Teixeira, E. A., Notas sôbre a bauxita em Poços de Caldas. Mineraçào e Metalurgia, vol. 6, no. 34, pp. 159–163, Sept. 1, 1942.

[9] Clarke, F. W., Data of Geochemistry; 5th edit., U. S. Geol. Survey Bull. 770, pp. 503–504, 1924.

[10] Op. cit., p. 10.

THE FOUNDATION OF HALES BAR DAM.

JOHN W. FRINK.

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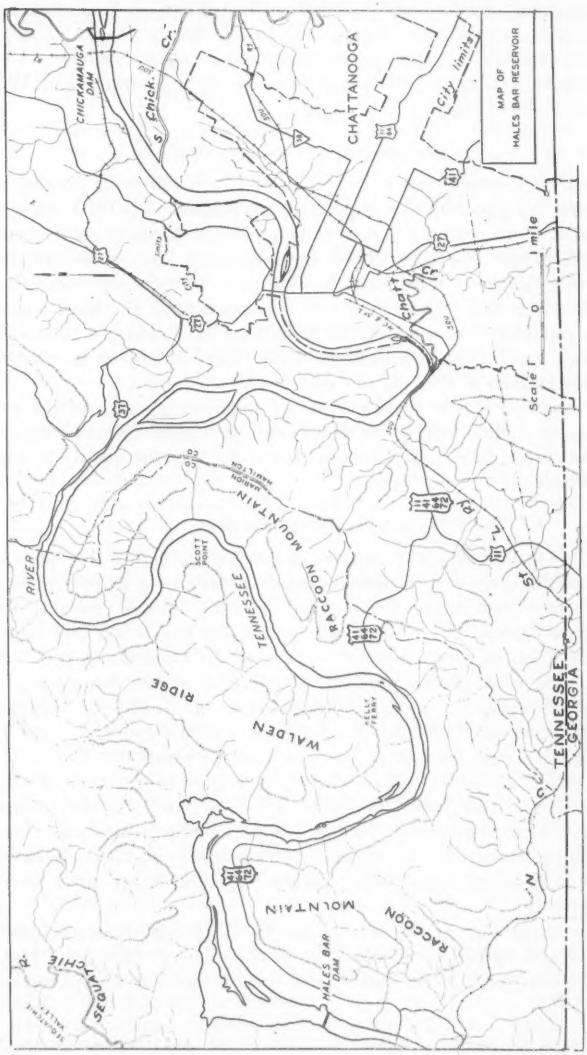
ABSTRACT.

Hales Bar Dam was built on cavernous Mississippian limestone, by a private power company, from 1905 to 1913. Inadequate foundation treatment and lack of realization of the true conditions beneath the dam resulted in serious leakage through the foundation. Several attempts were made to stop the leaks, but none were successful until a four-year repair program was undertaken by the Tennessee Valley Authority, in 1940. Most of the caves were the result of solution of shattered limestone along two small thrust faults.

INTRODUCTION.

HALES Bar Dam is located in Marion County, Tennessee, at mile 431.1, on the Tennessee River, thirty-three miles downstream from Chattanooga (Fig. 1). The dam was built by the Chattanooga and Tennessee River Power Company, between 1905 and 1913, and was acquired by the Tennessee Valley Authority in 1939.


MAP OF HALES BAR RESERVOIR
CHATTANOOGA
City limits
CHICKAMAUGA DAM
S. Chick. Cr.
Chatt. Cr.
Scale
0
1 mile
TENNESSEE
GEORGIA
TENNESSEE RIVER
RACCOON MOUNTAIN
RACCOON MOUNTAIN
WALDEN RIDGE
SUCK CREEK MOUNTAIN
HALES BAR DAM
SOUTH PITTSBURG
SOUTH PITTSBURG HILL
SOUTH PITTSBURG MOUNTAIN
NORTH CHATTANOOGA
SIGNAL MOUNTAIN
LOOKOUT MOUNTAIN
MISSIONARY RIDGE
MISSIONARY RIDGE
MISSIONARY RIDGE

The dam is in the Cumberland Plateau Province on the southeast flank of the Sequatchie anticline and at the downstream end of the Tennessee River gorge through the Walden Ridge section of the province. The channel through this section was narrow, crooked, and in places shallow. Velocities were excessive, reaching 5.33 feet per second in low water, and 19.18 feet per second at flood stages.

EXPLORATION FOR DAM SITE.

In the 19th Century, the U. S. Corps of Engineers made several surveys to determine the possibility of improving navigation. In 1900, these studies culminated in a recommendation of a dam to provide slack water throughout most of the gorge. Several Chattanooga business men conceived the idea of generating power at the proposed dam, and they entered into a contract with the Government. Hales Bar site was selected as the most satisfactory of several considered because of the possibility of building a relatively high dam on rock foundation at a location where there would be less backing up of flood waters than at sites farther upstream.

It is obvious that the physiography of the river gorge and the presence of bed rock at shallow depths were the only geological factors considered in locating the dam. In no case, so far as is known, was the quality or condition of rock considered.

CONSTRUCTION PERIOD.[1]

Special Features.—At the time of construction, Hales Bar was a great precedent-setting project. It was the first instance of a private power company building a dam across a navigable stream. It was probably the first multi-purpose dam in the country, being built for navigation and power. It was the first dam in which caissons were used for penetrating rock. It was one of the first examples of pressure grouting in a dam foundation. With the possible exception of some high-head dams in the Rocky Mountains, it had the greatest power installation of any dam in the country. The project had the highest single lift lock in the world at the time.[2]

Construction Progress.—The work was begun in October, 1905, with the expectation of completion in 1907. However, in June, 1910, the earth embankment, lock, transformer house, and part of the powerhouse were the only completed sections of the project. The progress was accomplished after five years of grueling work, which proved too much for three successive contracting firms.

The consulting engineering firm of Jacobs and Davies undertook the work at this time and agreed to complete it at the owners' expense. The work progressed more speedily thereafter, and the project was completed on November 4, 1913.

[1] The following discussion is the result of compilation of data from many papers, reports, and drawings, mostly unpublished. The author believes it to be the only complete account of the construction and leakage history of Hales Bar Dam yet written.

[2] Leggett (8), states that the Kinder embankment in England (1903–1905) was the first instance of pressure grouting, to his knowledge, and that the Estacada Dam in Oregon (1912) was one of the first cases in the United States.

The structure was financed by the Chattanooga and Tennessee River Power Company, but safety of all structures was the responsibility of the U. S. Army Engineers, who in a large measure supervised the entire construction program.

Foundation Conditions and Treatment.

Earth Embankment and Powerhouse.—According to progress drawings, the core wall of the earth embankment was founded on rock from the powerhouse eastward to station 6+63, on gravel to station 4+23 and on clay from there to the east abutment. In addition, sheet piling was driven to rock between station 3+70 and 6+75.

The foundation of the transformer house was a conglomerate mass of boulders and fissured limestone filled with quicksand and green clay, and bearing considerable water. As far as is known, no grout was used in the transformer house or embankment foundation.

The powerhouse excavation was carried to elevation 545–548 from the original rock surface at elevation 582–585. When the excavation was completed, leakage through the rock amounted to 15,000 gallons per minute. Part of the flow came from seams and fissures in the sides of the excavation, but most of it came from a 1 to 6 foot cavity at elevation 537–545, which extended almost continuously beneath the foundation. This is apparently the same bedding plane cavity in the lower part of the coarse crystalline limestone west of station 12+50 beneath the spillway (Fig. 2).

The leakage was so bad that it was not possible to grout against the water pressure, so six-inch holes were drilled twenty feet deep within the unwatered cofferdam, and pipes were sealed into the tops of the holes. The cofferdam was flooded, sometimes to a higher level than the water outside, and compressed air was forced into the holes to give some idea of the extent of cavitation. The holes were washed with water under pressure and grouted in charges forced in by compressed air. Low pressures were used on the first charges, but were raised as the holes became tight, to a maximum of seventy-five to eighty pounds.

The excavation was made by alternately drilling and grouting. When a depth was reached at which the foundation was considered satisfactory, a two-foot slab of concrete was poured over the entire surface. This effectively curbed the leakage so that grouting could be carried on through pipes embedded in the slab without flooding the cofferdam. The grouting continued for four months using about 25,000 bags of grout. At the conclusion of the program, practically all leakage was stopped.

Accounts published at the time (7)[3] state that all cavities were washed clean before they were grouted; however, progress drawings indicate that this policy was not strictly followed.

Lock.—Beyond one mention (10) of fissures in the lock foundation, there are no records pertaining to the condition or treatment of the rock in this section of the dam. Inasmuch as the excavation was completed in 1909 and

[3] Numbers in parentheses refer to references at end of article.

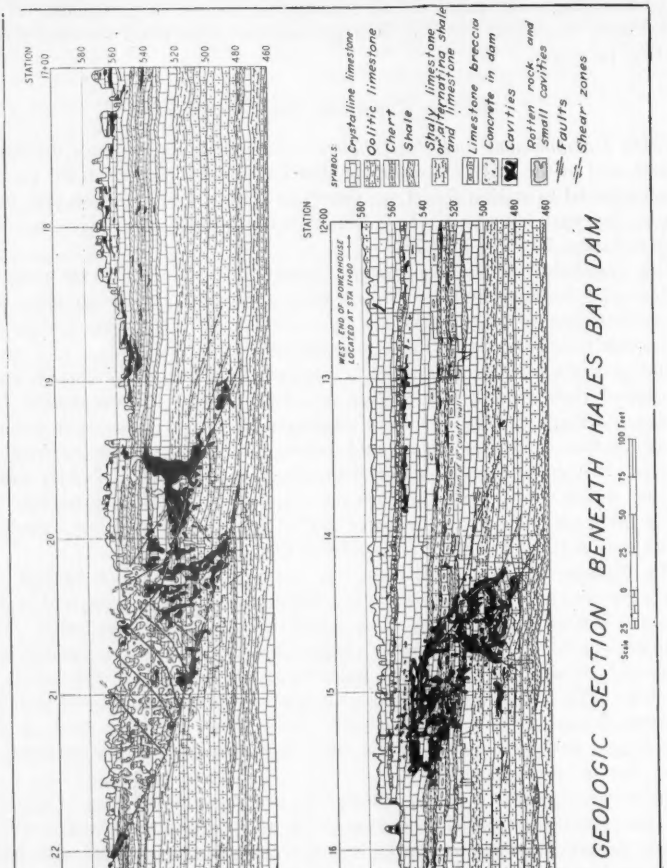


FIG. 2.

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the structure was virtually completed in 1910, we may assume that little trouble was encountered here.

Spillway—Non-Caisson Section.—The foundation conditions beneath the eastern portion of the spillway were much the same as those beneath the powerhouse except that there was less trouble with water. The treatment methods here were similar to those used in the powerhouse area with the omission of the concrete slab. It is stated (20) that 100,000 bags of grout were used, but this figure might include the powerhouse area.

One hole at station 14+60, which was drilled to elevation 533, penetrated a large cavity and took 12,240 bags of cement. There is no record of any other hole being drilled to the same depth nearby.

Spillway—Caisson Section.—As soon as work began in the western section of the dam, it was realized that the condition of the rock was much worse than anything yet encountered. Not only was the fissuring more extensive, but all cavities were filled with clay which precluded grouting unless the clay could be washed out. Nevertheless, a vigorous program of drilling and grouting was followed until the spring of 1911, when the builders realized it would be useless to proceed further, and decided to use pneumatic caissons to reach solid rock.

Apparently a sporadic attempt was made to explore this newly discovered cavernous area, for eight diamond core drill holes were put down as far as elevation 476, between station 15+59 and 17+17. In addition, one drill hole located fifteen feet upstream from the dam face at station 19+43 was drilled to elevation 512 and encountered a single cavity extending the last thirty-two feet of its length. This opening is the upstream extension of the large cave shown in Fig. 2. No other hole is known to have been drilled to check this finding and no grout was introduced.

Much of the rock in the caisson section had the appearance of a huge pile of boulders, each completely surrounded by clay. In two or three places, a steel rod was churned into the crevices more than fifteen feet. The condition improved with depth so that the rock on which the caissons were founded was considerably better than that above, but it was still broken up into blocks, the largest of which were twenty to thirty feet across. Between stations 20+10 and 21+70 many of the larger blocks had settled and tilted because of lack of support.

At first, small reinforced concrete caissons were used, with dimensions of forty by forty feet on the upstream side, and thirty by thirty-two feet on the downstream row. After twenty-one of these were built, it was decided to complete the job with five seventy-two by fifty-four foot caissons, necessitating only one row. During construction and sinking, the caissons were protected from flood flows by a cofferdam. Originally, they were sunk with a one-foot space between them, but difficulties encountered in sealing the space brought about an increase, first to eighteen inches, and then two feet.

Excavation was carried out by small air drills and small charges of dynamite until a foundation acceptable by the Government engineers was reached. Holes were drilled eight feet below this point and were piped for later grouting through the air locks. As the working chambers were only

four and one-half feet high, the caissons had to be hung several feet above the bottom to provide working room (7).

All fissures were cleaned out to a depth of two to five feet, and the rock was cleared away from under the caisson cutting edge a short section at a time, and replaced by a cement bag wall which was plastered on the inside face. The working chamber was filled with concrete nearly to the top, then the small space left was grouted through the pipes built into the caisson roof, and, finally, the drill holes were grouted through the pipes which had previously been extended from them up through the air lock.

The narrow spaces between the caissons were washed with water under high pressure. Then a four-foot concrete cap, in which three-inch pipes were placed on three-foot centers, was built over the space and grout was introduced through the pipes. Additional holes were drilled through the concrete and the grouting was repeated until less than fifteen bags of cement was accepted at one time. Spaces wide enough to admit a man were cleaned by hand, and grout pipes were driven at least to the level of the lower caisson cutting edge. The space was filled with concrete and then grouted. The large spaces were capped by concrete slabs with air shafts and were cleaned by hand under compressed air and treated much as beneath regular caissons.

Summary.—In summary, it may be said that the drilling and grouting program was, as a general rule, carried deeper in the solid rock than in the cavernous area. Certain curious coincidences are found. For instance, the grouting holes were not deep enough to reach the cavernous area between 14+50 and 15+50, except for a solitary hole which accepted over 12,000 bags of grout, the most easterly diamond drill hole is just west of the cavernous area, the leakage area around 13+50 was avoided, and one hole encountered a thirty-two-foot cavity at station 19+43, but no other drill holes were located so as to check this discovery.

HISTORY OF LEAKS AND REMEDIAL TREATMENT.

1913–1920.—The first outflow of water was noticed about November 15, 1913 (less than two weeks after completion of the project), below the eastern cavernous area. Investigation revealed more leaks downstream from the gravel bar. The leaks increased in size and number for several weeks. The first suction was found a few days later about thirty feet east of the upper lock guide wall.

Rocks were dumped into the crevice where the inflow had been discovered and gravel and clay were placed on top. This increased the difficulty as the water only succeeded in enlarging the intake.

During the summer of 1914, the river bottom above and below the dam was sounded to locate all suctions and boils. In 1915 rags were placed in the suctions and were covered with concrete. This plan was modified later in that the suction was surrounded by concrete and the work was carried toward the center. The only result was that once a suction was stopped, the water would break through at some other point.

This period during which the character of the leakage developed and many types of treatment were attempted, has now become legendary. Stories re-

late in glowing detail the dumping of bales of hay, old mattresses, chicken wire, and carloads of corsets into the suctions. Some of these stories are undoubtedly true, and some of them might well be mere figments of imagination.

Asphalt Grouting Program, 1919–1922.—Prior to 1919, all attempts to stop the leaks were unsuccessful. In fact, the volume of water passing beneath the dam increased every year. At this time, George W. Christians (3) conceived the idea of drilling holes from the inspection tunnel in the dam into the rock and pumping hot asphalt into crevices.

The great advantage of asphalt over other types of grout, was that it could be placed in cavities with flowing water. The hot asphalt would be chilled by contact with water, and the outside of a globule would solidify, thus blocking the passage. The inside of the mass would remain fluid, and addition of more hot asphalt would expand the mass until it filled the entire cavity. Other advantages were claimed for this type of grouting, but the results of the T.V.A. drilling program showed that these claims were not justified.

The asphalt was heated in kettles on the lock wall, pumped through an electrically heated pipe to the hole, then forced down a one and one-half inch pipe to the cavities across which the pipe was perforated with three-quarter inch holes. A wire inside the pipe could be heated by electricity and served to keep the asphalt liquid until it passed out of the pipe. This wire could also be used to reheat the solidified asphalt in the pipe so that additional grouting could be carried on at a later date.

Total drilled footage in this program was 6,266 feet. The average depth of the holes was 92 feet, the greatest, 134 feet. Forty-five holes were grouted, using 78,324 cubic feet of asphalt, introduced under pressures as high as 200 pounds per square inch.

In 1919, there were nine small boils below the eastern cavernous area but in 1922, only one was still visible. At the beginning of the program, eight boils, some very large, were downstream from the western cavernous area. Only one of these was eliminated by the grouting, but all were considerably reduced in size.

Christians claimed that an entire hole could be treated at one time with asphalt. Results of the drilling program in 1941–1944 showed conclusively that asphalt will leave the pipe by the first perforations it reaches so that only the upper cavities are grouted. Christians drilled holes to the bottom of the cavernous zones in most cases, but the drilling in 1941–1944 seldom recovered asphalt below elevation 530, and effective quantitities of it were always above elevation 540. As a matter of fact, the engineers of the Tennessee Valley Authority discovered that ten to fifteen feet was the maximum length of perforated pipe that could be used satisfactorily.

Christians also claimed that holes for asphalt grouting need not be spaced as closely as those for cement grouting. The T.V.A. engineers, however, found that effective results were obtained only when asphalt grouting holes were placed on five-foot centers.

Exploration, 1930–1931.—Soon after Christians' program was halted, the

volume of leakage began a gradual increase until in 1929, it was at least as great as in 1919.

In 1930, a thorough exploration program was begun in an attempt to locate all leakage inlets and outlets. Detailed soundings were made of the river bottom, above and below the dam. All areas which were suspected of containing suctions or boils (Fig. 3) were carefully explored, sometimes by a diver; and maps and cross-sections were drawn of them. Dye and oil were introduced into large suctions and connections were thus established between them and the outlets below the dam. The volume of outflow of each boil was estimated and the velocities were measured with a current meter. No corrective work (5) was undertaken at this time.

FIG. 3. Leakage Boil J, November 12, 1942.

Volume of Leakage.—Several estimates of the leakage volume have been made since 1921. As no two methods are the same, no comparison between the results can be made. The early figures arrived at varied from 100 to 1,200 c.f.s. Careful measurements made by the T.V.A. and U. S. Geological Survey in 1939 resulted in two similar answers arrived at by using different assumptions of flows which could not be measured. These volumes were 1,720 and 1,650 c.f.s., or 10 per cent of the normal low water flow of the river.

Leakage Inlets and Outlets.—Surveys of the inlets and outlets were made in 1914, 1915, 1920, 1921, 1922, 1923, 1930, and during the T.V.A. program from 1940 to 1944. As a result, a reliable record of the location of the boils and suctions has been preserved. Inlets and outlets of the leakage system are confined to definite zones determined by faulting and to a lesser extent by location bedding plane cavities. Most of the boils shift from time to time—in fact, several boils changed location during the T.V.A. correction program. However, a few seem to maintain their location over long periods of time.

Generally speaking, the size and number of the boils had increased steadily since the dam was completed until 1930, except for the temporary decrease as

a result of the asphalt grouting program. After 1930, there was considerable change in location of the boils, but apparently little in the volume of leakage.

T.V.A. PROGRAM, 1940–1944.

The Tennessee Valley Authority purchased Hales Bar Dam from the Tennessee Electric Power Company on August 16, 1939. At that time, the leaks were flowing with greater volume than at any previous time. There were thirteen known boils below the dam. The stability of the foundation was seriously questioned, even though all earlier investigations had pronounced it safe.

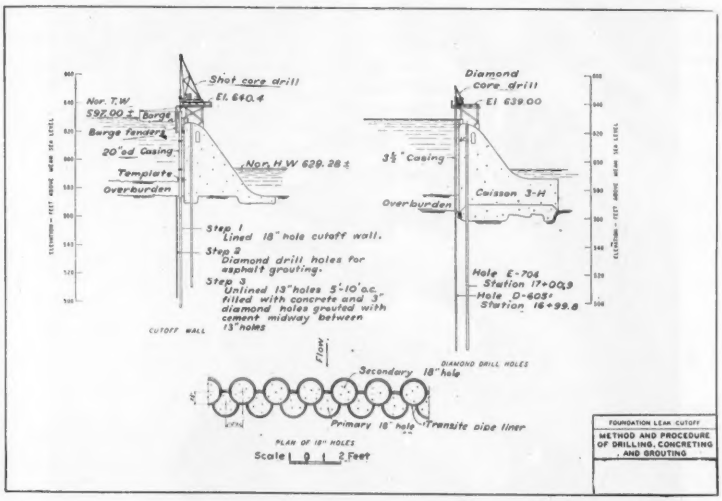

FIG. 4. Treatment of cavitation. Erratum: In upper left corner *Nor. T. W. 597.00* ± and *Nor. H. W. 629.28* ± should be reversed.

Investigations were begun immediately after acquisition of the dam to determine the extent of the leaks and the proper methods for remedying them. In November, 1940, experimental drilling was begun to test the feasibility of building a cut-off wall without emptying the reservoir. This work continued for about eight months, when the main outlines of the present procedure were established, and the work to stop the leaks was begun in earnest.

The program, as finally worked out, was as follows: Three-inch diamond drill holes were drilled along the upstream face of the dam for determination of the extent of the cavernous areas. The relatively sound portions of the foundation were then grouted.

In the areas of serious cavitation, the treatment was as follows (Fig. 4):

1. In particularly cavernous areas where grouting was not successful, a

cut-off wall of overlapping eighteen-inch holes was made by drilling, lining, and concreting these holes (Fig. 5).

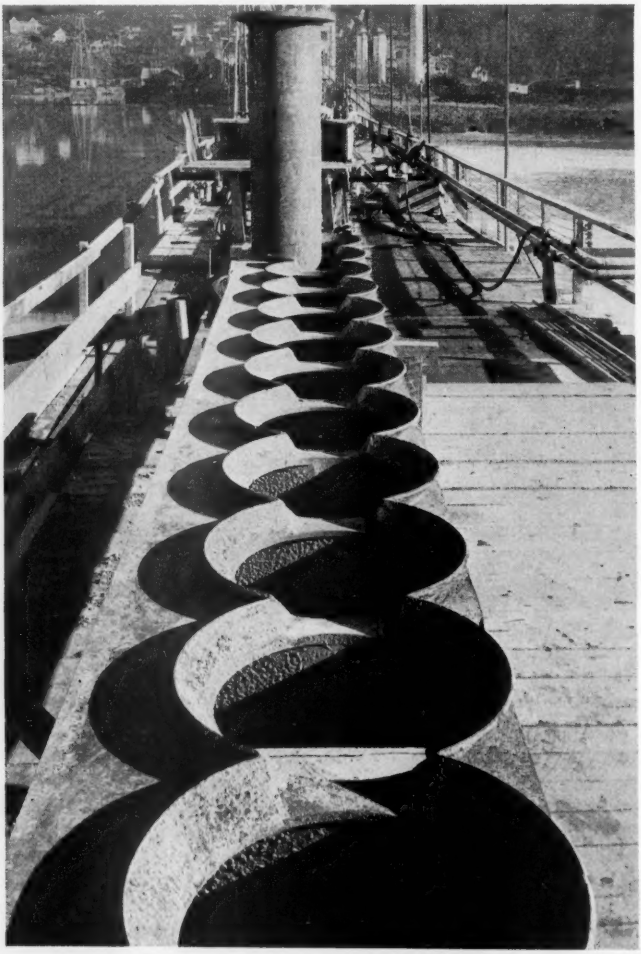

FIG. 5. Template for spacing casing for drilling 18-inch cut-off wall.

2. Diamond drill holes were located upstream from the cut-off wall and were asphalt-grouted for the purpose of sealing any gaps between the liners of the eighteen-inch holes.

3. When the preceding steps were completed, the foundation beneath the dam was consolidated as follows:

a. In sections where grouting alone was sufficient to stop the leaks, diamond drill holes were drilled through the dam four or five feet downstream from the upstream face and were grouted.

b. In sections where steps 1 and 2 were necessary, thirteen-inch diameter shot drill holes were drilled five feet downstream from the upstream face. These were Tremie concreted without being lined in order to fill the major cavities.

c. Diamond drill holes were placed between the thirteen-inch holes and grouted to consolidate the dam foundation (18).

The geologists logged the core recovered from all types of holes. Diamond drill holes were placed on two and one-half and five-foot centers in the grouted areas and on five-foot centers for asphalt grouting the cavernous areas. Since there was virtually no core loss, excellent structural control could be obtained. The core from the overlapping eighteen-inch holes provided an excellent outline of the cavitation in one plane in spite of considerable core loss in some areas.

At the conclusion of the program, all visible signs of leakage disappeared except for one small boil below the gravel bar. The possibility that a very small channel fed this boil made further attempts to stop it uneconomical. The program may also be considered successful from the standpoint of security of the dam itself.

GEOLOGY OF THE DAM SITE.

Physiography.—At the dam site, the Tennessee River is flowing southwest in a narrow strike valley cut in the Bangor limestone (Fig. 6). The

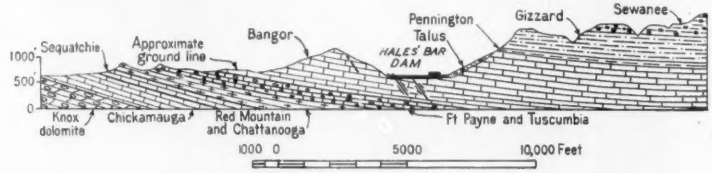

FIG. 6.

dam's east abutment is Raccoon Mountain, part of the Cumberland Plateau, rising to elevation 2,000 feet and capped by cliffs of Pottsville sandstone and conglomerate. The lower two-thirds of the slope is covered with talus against which the earth embankment of the dam abuts.

Stratigraphy.—The dam is built upon the Bangor (unrestricted)[4] limestone of Mississippian Age.

A total of about 160 feet of the Bangor section has been encountered by drilling beneath the dam during the present program. The entire section is

[4] Butts (2) (pp. 177–199) restricted the name to the upper part of the formation and divided the rest into six new formations which except for the Gasper are not distinguishable lithologically in this vicinity.

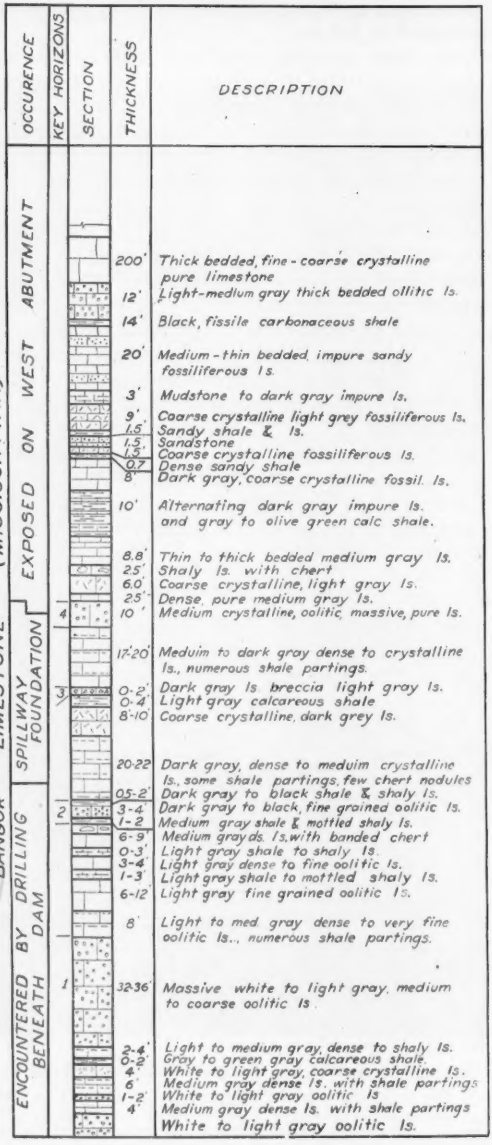
BANGOR LIMESTONE - (MISSISSIPPIAN)
ENCOUNTERED BENEATH DRILLING BY DAM
SPILLWAY FOUNDATION
EXPOSED ON WEST ABUTMENT
OCCURENCE
KEY HORIZONS
SECTION
THICKNESS
DESCRIPTION
200' Thick bedded, fine - coarse crystalline pure limestone
12' Light-medium gray thick bedded ollitic ls.
14' Black, fissile carbonaceous shale
20' Medium - thin bedded, impure sandy fossiliferous ls.
3' Mudstone to dark gray impure ls.
9' Coarse crystalline light grey fossiliferous ls.
1.5' Sandy shale & ls.
1.5' Sandstone
1.5' Coarse crystalline fossiliferous ls.
0.7 Dense sandy shale
8' Dark gray, coarse crystalline fossil. ls.
10' Alternating dark gray impure ls. and gray to olive green calc shale.
8.8' Thin to thick bedded medium gray ls.
2.5' Shaly ls. with chert
6.0' Coarse crystalline, light gray ls.
2.5' Dense, pure medium gray ls.
10' Medium crystalline, oolitic, massive, pure ls.
17-20' Meduim to dark gray dense to crystalline ls., numerous shale partings.
0-2' Dark gray ls breccia light gray ls.
0-4' Light gray calcareous shale
8-10' Coarse crystalline, dark grey ls.
20-22' Dark gray, dense to meduim crystalline ls., some shale partings, few chert nodules
05-2' Dark gray to black shale & shaly ls.
3-4' Dark gray to black, fine grained oolitic ls.
1-2' Medium gray shale & mottled shaly ls.
6-9' Medium gray ds. ls. with banded chert
0-3' Light gray shale to shaly ls.
3-4' Light gray dense to fine oolitic ls.
1-3' Light gray shale to mottled shaly ls.
6-12' Light gray fine grained oolitic ls.
8' Light to med. gray dense to very fine oolitic ls.., numerous shale partings.
32-36' Massive white to light gray, medium to coarse oolitic ls.
2-4' Light to medium gray, dense to shaly ls.
0-2' Gray to green gray calcareous shale.
4' White to light gray, coarse crystalline ls.
6' Medium gray dense ls. with shale partings
1-2' White to light gray oolitic ls
4' Medium gray dense ls. with shale partings
White to light gray oolitic ls.

FIG. 7.

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composed of light to medium gray, dense to crystalline, sometimes oölitic, massive-bedded limestone, with a few zones of calcareous shale. On superficial examination, the entire section appears to have the same lithology, and in the field would certainly be mapped on one unit. In order to determine the structure, the lithology of the diamond drill core was examined in detail with the idea of dividing the sequence into as many lithologic units as possible.

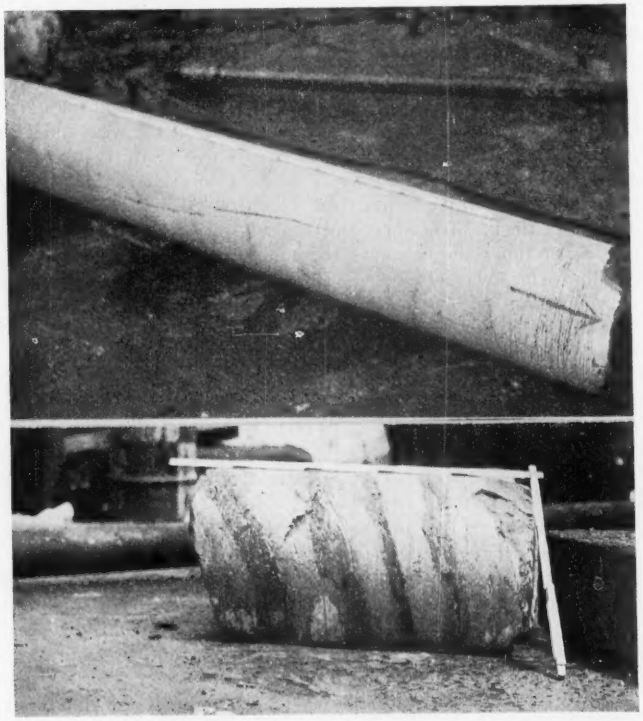

FIG. 8. (*a*) 8.9-foot piece of core; (*b*) chert bands below black oölite.

Those with a distinct lithology and definite top or bottom limits were valuable for correlation purposes, but they have no other stratigraphic significance. The detailed section in Fig. 7 gives the essential data for recognizing any units in the vicinity of the dam. The notes to follow merely point out additional facts about the key horizons.

The Gasper is the deepest rock penetrated by drilling. Its uppermost zone consists of from thirty-two to thirty-six feet of massive crossbedded, white to light gray oölitic limestone Fig. 8A. The individual oölites are

usually lightly cemented together and apparently are in no way altered from the time of original deposition. These two factors produce a light-weight, porous limestone which is very easy to drill. The top few feet of the oölitic zone exhibits numerous vertical joints, many of which are weathered, but few are open. This key horizon is designated as No. 1.

The top of the oölite is easy to recognize. The lithology is distinct and the contact with the overlying limestone is sharp, but the bottom of the zone is somewhat gradational into shaly limestones and shales beneath, also Gasper in age. The latter beds, which are reached by drilling only beneath the western half of the spillway, are somewhat discontinuous and grade into one another. The Gasper nowhere forms the acutal foundation of the dam. Its top occurs at elevation 485.0 at the east end of the spillway and rises gradually (except in the two faulted areas) to elevation 530.0 at the west end (Fig. 2).

The second key horizon occurs from twenty-five to thirty feet above the top of the Gasper. It is dark gray to black, fine grained, firmly cemented oölitic limestone from three to four feet thick, framed by two shale beds from one to two feet thick. The upper one is dark gray to black and grades into overlying dense limestone becoming difficult to recognize in the western half of the dam. The lower shale bed is light gray with a mottled appearance caused by breaking up and reworking of the originally deposited lime mud. Both shale beds, but especially the lower one, are mostly weathered and cavernous. Immediately below the lower shale is a four- to five-foot zone, containing many massive bands of chert, which often serves as a guide when the beds above are weathered out (Fig. 8B). This key horizon rises gradually from elevation 521.0 at station 11+00 to elevation 557.0 at station 23+00. It served as an excellent marker in determining the structure in the faulted areas. It is the lowest rock upon which the dam actually rests, forming the foundation between stations 19+20 and 19+40.

Beneath the eastern half of the dam, thirty to thirty-five feet above the black oölite zone, occurs a light to medium-gray dense limestone (key horizon No. 3), from 0.5 to 2.0 feet thick, containing numerous brecciated fragments, one-eighth to one inch thick, of very dark gray, dense dolomitic limestone. This bed is underlain by a light gray, calcareous shale which thins westward and is much weathered. The shale and the breccia zone above in places are deformed, showing dips as high as thirty degrees for a few feet laterally. The cause of such an evenly distributed breccia zone is difficult to explain (14). The key horizon is found at elevation 550.0 at station 11+00 and rises gradually to elevation 565.0 at station 15+65 where the top of rock drops abruptly. Beyond there, the zone is encountered only in ledges which were not excavated at the time of construction and are now above the base of the dam. This horizon is above the fault zone in the eastern area.

The uppermost key bed (No. 4) beneath the dam is a ten-foot zone of light gray, crystalline to oölitic, massive limestone, very similar in lithology to the Gasper. This bed forms the dam foundation east of station 12+50.

Geologic Structure.—As mentioned before, Hales Bar Dam is built on the southeast flank of the Sequatchie anticline. The general picture is that of a sharp-crested anticline with a very broad, flat syncline extending south-

eastward almost to the Wills Creek Valley. The axis of the anticline trends approximately N 25° E. The rocks dip twenty degrees to the southeast along the anticlinal axis, but the dip decreases rapidly eastward until at the dam site it is three to five degrees. Beneath the dam itself the dip varies from horizontal to five degrees, with occasional cores recovering thirty-degree dips in the faulted areas.

There are no major faults near the dam, but minor faults with displacements of ten to thirty feet are abundant. Strikes are always nearly parallel to that of the rocks. Reverse faults dipping thirty degrees or more are the most common type. One normal fault occurs at the west abutment of a toll bridge 1.5 miles below the dam, and several smaller ones occur in a group three miles below the dam in a railroad cut. These are associated with a large fault of unknown displacement on which striations, appearing to be poorly preserved slickensides, show nearly horizontal movement.

Beneath the dam are two important fault zones each characterized by a large east-dipping thrust fault opposed by several small west-dipping thrusts beneath it. These small thrusts terminate upon contact with the larger one at the upper end and against a poorly defined gently east-dipping shear plane at the lower end. The major cavitation beneath the dam is confined to the area between the large thrust above and the shear plane below (Fig. 2).

The major fault in the eastern area has a displacement of about fifteen feet on marker bed 2. Here the fault is dipping 45°. At depth, the dip decreases until the faulting disappears in the shaly limestone of the Gasper. Immediately above bed 2, the fault zone becomes nearly horizontal and the cavitation induced by it cannot be distinguished from that formed along bedding planes. The three opposing small faults all dip forty-five degrees or more and have displacements of three to five feet. A shear zone showing little measurable displacement, dipping fifteen degrees to the east, passes beneath these small thrusts. Its western extremity seems to be at elevation 497.0 at station 15+00. The higher cavities west of station 14+80 have a sloping bottom which may also mark a shear zone.

Faulting in the western area is considerably more complicated. First, a fault zone dipping twenty-five degrees east extends from elevation 480.0 at station 19+00 to elevation 520.0 at station 20+00 where it steepens considerably, probably to sixty degrees. The displacement is about twenty feet at station 19+50 and the vertical throw is ten feet. At station 20+20 where the dip is sixty degrees, the displacement is about twelve feet, but vertical throw is ten feet. There are two or three branches to this fault as shown on Fig. 2. The opposing faults are similar to those in the eastern area, each dipping forty-five degrees to the west with a displacement of two to five feet. The shear plane along the bottom of the cavernous zone is easily distinguished, having a displacement of about three feet in the black oölite bed and easterly dip of fifteen degrees until it disappears in the shaly limestone below elevation 480.0.

The most common faulting might more correctly be called shearing. The sheared zones are very numerous on the west abutment and beneath the dam where they have about the same strike as the strata and generally dip from

twenty to thirty degrees either to the east or west, those to the east being more common. All of these planes have had reverse or thrust movement as is shown by the well developed slickensides. Rare offset fossils and calcite veins show displacements as high as one-eighth inch. These zones are related to the major fault planes, but they do concentrate in certain beds (particularly the black oölite) which are especially susceptible to shearing.

Reverse faults do not cause cavitation directly, but by shattering the rock, form many porous planes inviting water percolation. This is true, not only along the fault plane itself, but along associated shear planes and gash joints (the latter actually being open) associated with faulting. At Hales Bar, shattering has been great enough near all the major fault planes to invite solution.

On the west abutment is a well-developed system of joints of which the strike joints trend about N 20° E, and generally dip eighty degrees southeast, while the dip joints are more numerous and in the abutments show greater solution. Both types of joints no doubt account for some leakage beneath the dam.

Physical Qualities of the Rock.—Where unweathered, the Bangor limestone is perfectly stable under any dam load. The massive bedding of the limestone and the scarcity of shale beds produce an excellent foundation. The Bangor limestone is exceptionally pure, as the representative analyses given in the following table indicate. Unfortunately, most of these were made before necessity of detailed lithologic work was realized, so that individual horizons cannot always be identified.

TABLE OF CHEMICAL ANALYSES

	Percentage						
	1	2	3	4	5	6	7
Silica (SiO_2)	0.20	0.10	4.8	23.7	58.0	4.11	10.44
Alumina (Al_2O_3)	0.64	0.65	1.7	6.7	16.5	0.87	2.09
Iron oxide (Fe_2O_3)	0.33	0.20	0.52	2.5	5.2	1.08	1.56
Lime (CaO)	54.9	55.3	50.5	32.4	3.9	31.57	29.85
Magnesia (MgO)	0.73	—	—	3.7	2.7	18.39	16.43
Phosphorus pentoxide (P_2O_5)	—	—	—	—	—	0.02	0.04
Titanium dioxide (TiO_2)	—	—	—	—	—	0.07	0.09
Calcium carbonate ($CaCO_3$)*	98.0	98.7	90.1	57.9	7.0	56.34	53.27
Magnesium carbonate ($MgCO_3$)*	—	—	—	—	—	38.46	34.36
Moisture, 110° C.	0.05	—	—	—	2.9	0.07	0.26
Loss on ignition, 110–1000° C.	43.7	—	—	—	7.3	43.74	39.34

* Calculated from oxide.

1. Limestone.
2. Oolitic limestone—Gasper.
3. Crystalline limestone, ten feet belowbreccia.
4. Shale, below black oolite.
5. Shale.
6. Limestone breccia—fragments.
7. Limestone breccia—matrix.

Rock Weathering.—As a general rule, these very pure limestones are removed by solution rather than undergoing decay. This is because decom-

position of the rock results in the solution of calcium carbonate, leaving only the negligible impurities as residue. Any surface reached by circulating water will be clean, fresh, and smooth. Only sides of filled cavities, small joints, and some bedding planes show weathering. Even then, it is only a rusty surface extending a fraction of an inch into the rock. The weathered bedding planes are confined to the upper thirty to fifty feet of rock beneath the dam.

The shales, strangely, are commonly weathered. Certain beds, notably just below the breccia, and below the black oölite, are seldom in a completely fresh state. In the absence of an active water current, they disintegrate completely before being removed. Weathering decreases with depth, but it is limited by no line due to lithology, such as impervious shale beds.

The chert bands and single shale partings in the limestone act as resistant layers and protrude from the reduced surfaces of the limestone.

Rate of Limestone Solution.—The extreme purity of the limestone makes a very rapid rate of solution possible which in one instance was measurable.

In drilling the eighteen-inch cut-off wall between station 14+70 and 14+80, more than a year elapsed between the drilling of the primary and the interlocking secondary holes. The rock in this area was quite cavernous and a strong water current was present in the cavities.

When the secondary holes were drilled, it was noticed that the rock surface, which had been cut by the drilling of the primary holes, was pitted and in places reduced as much as one-tenth to one-eighth inch by solution (13).

Thus we may say that the maximum rate of solution is one-tenth inch a year. Fox (11) has demonstrated solution of boulders in the Tennessee River at Watts Bar Dam to amount to one-half inch in twenty-five years. In this case, the rock is Nolichucky limestone—much less soluble than the Bangor—and it was above low water, therefore, not subject to uninterrupted solution.

The rate of solution described is not comparable to that under normal groundwater conditions, but it indicates the rate of solution of a very soluble limestone under conditions of free water circulation.

Cavities.—The location of cavities beneath Hales Bar Dam is dependent upon three different types of geologic structures: (1) bedding planes, (2) joints, and (3) shatter zones associated faults.

Bedding plane cavities at Hales Bar are the result of selective weathering or solution acting in one of two distinct processes. First, water percolated along an actual bedding plane where cementation of the rock is poor or where impurities formed a pervious layer. The action of this process is verified by numerous weathered bedding planes at shallow depths beneath the dam. The bedding planes cavities (between stations 14+70 and 15+50 at elevation 555.0) that occur at the contact between the coarse crystalline limestone and the dense limestone below, are good examples of this type of origin (Fig. 2). The numerous cavities above the black oölite between station 16+00 and station 19+00 might also be assigned to this type.

The second type of bedding plane weathering is caused by weathering or solution of particularly susceptible beds such as soft shales or exceptionally soluble limestones. Examples of such cavities are those formed in the shale

bed below the breccia and those above and below the black oölite (elevation 520.0 at station 11+00, to elevation 560.0 at station 23+00).

In all previous experience with dam foundations, shale beds have proved to be impervious to water, generally forming limits to cavity zones, and were seldom cavernous themselves. The shale at Hales Bar acts contrary to all previously encountered examples. It is more cavernous than the surrounding limestone and does not form a barrier to percolation of water. The bed just below the black oölite is largely made up of broken and reworked limestone with shaly material between the fragments. When this bed disintegrates, the shaly material decomposes and becomes soft, but the limestone fragments commonly remain unweathered. It is a fact that these shales are highly calcareous, which may in itself explain the strange phenomenon.

Joints play an important, but not easily determined, role in the cavitation. Numerous closed weathered vertical joints have been encountered and several open vertical joints from three to five inches were found by the large diameter drills in the cavernous area from station 14+25 to station 15+60. The drills recovered the side of a joint running parallel to the dam axis at the following places: station 14+85 to station 14+94, elevation 523.0–538.0; and station 14+98 to station 15+20, elevation 520.0–540.0, but mostly above 530.0.

Aside from the bedding plane cavities described above, all cavitation at Hales Bar Dam occurs in two localized zones limited on all sides by fault planes. One may theorize that a given cavity within these zones is a joint, or a bedding plane, but the fact remains that most individual openings are unexplainable in detail simply because their development has progressed beyond the point where the original weakness can be determined and because this weakness, whatever it was, was either originated or accentuated by faulting.

In the area from station 20+00 to station 21+50, few cavities are recorded by the large diameter drills, and core loss is excessive. The diamond drills indicate this area is a mass of weathered rock and small cavities, almost all of which are filled with mud. Although large cavities have not been developed in this area, weathering and solution have actually progressed further than in the eastern section. This is probably because of greater movement along the faults in the former case. However, it is difficult to imagine the reason for development of large clear cut cavities in the eastern area and small cavities with much rock weathering in the western area.

The holes drilled for foundation treatment give only a two dimensional picture of the cavitation. However, we are able to obtain a picture of the general strike of the cavernous zones when it is remembered that they are dependent upon the strike of the faults. A line drawn from the eastern extremity of the boils on the gravel bar through the outcrop of the large fault, station 20+20, beneath the dam to two old suctions, 1,600 and 1,900 feet upstream, has an approximate strike of N 27°, which may be assumed to be the strike of the fault and the cavernous zone. Credence is given to this idea by the fact that oil introduced into the suctions appeared in the boils. The oil also appeared in the boils below the eastern section of the dam, giving some evidence that the two zones converge upstream.

Dye and Velocity Tests.—During the present program, fluorescein dye frequently was introduced into all types of drill holes. From these tests, the

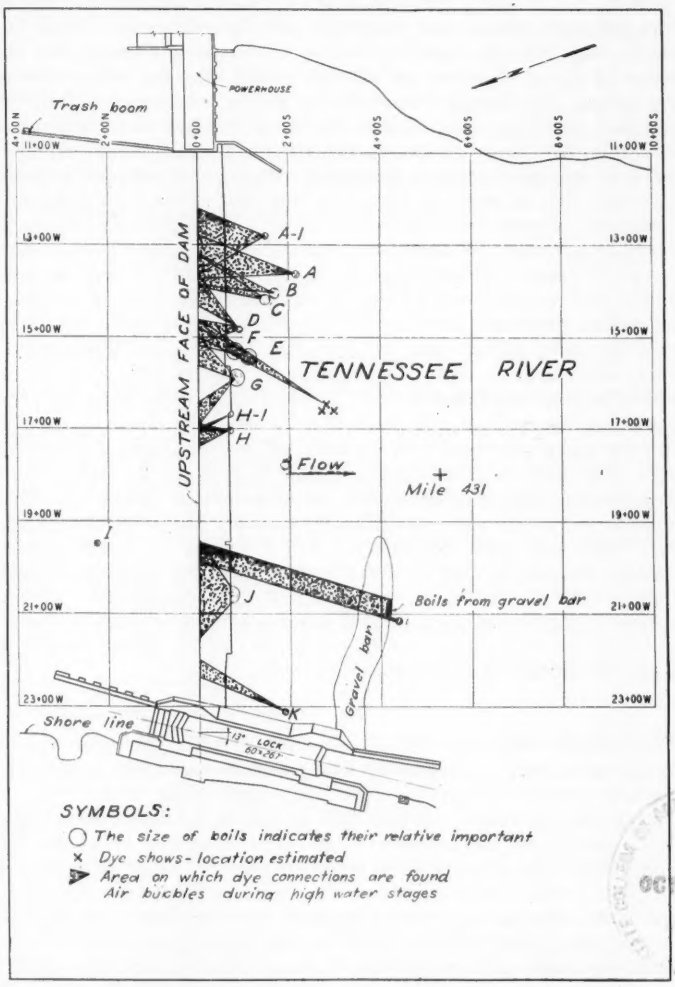

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FIG. 9. Rates and courses of water flow. Erratum: *Important* should read *importance.*

course of water flows and relative rates of flow could be determined. The results of these tests are shown in plan in Fig. 9. Attempts have also been made to show the dye connections in cross section, but no satisfactory results

could be obtained. However, this section, when studied in conjunction with Fig. 2, yielded much valuable information.

Boils A, A–1, B, and C received all of their leakage through bedding plane cavities below the breccia and associated with the black oölite. Boil D received its water from two sources: first, from the bedding plane cavities above elevation 550.0 east of station 14+20, and second, from the faulted area west of that station. Bedding plane cavities near the surface around station 17+00 caused the boils H and H–1. All of the rest of the boils in the eastern area received their flows from the faulted zone between stations 14+20 and 15+50. There is no particular elevation associated with any one leak, but in general, the dye flows are up the fault zones from the place where introduced to the boil, showing a tendency for the boil to be west of the point of introduction. The very deep cavities, below elevation 520 and east of station 14+60, showed no dye connections at all until after the cut-off wall had been put in place.

In the western area, boil J (Fig. 3) received water from all cavities between stations 19+43 and 21+50, but there were no shows east of 20+00 until after the area west of that point had been well treated. In other words, the flow was diverted to the east. The large cavity between stations 19+40 and 20+00 is the sole contributor to boil L. On July 1, 1944, when the present program was discontinued, this boil and those emerging from the gravel bar (which are really associated with it) were still active, although considerably reduced from their original strength. Boil K received its water through bedding plane cavities near the surface between stations 22+00 and 22+50.

Velocity tests were made in eighteen-inch holes with a standard velocity meter. These gave good indications of flow in one cavity, but the shape of the cavities changed so rapidly that the tests presented no general picture. The highest velocity recorded was 6 c.f.s., which is considerably below the theoretical velocity if the actual head of water is entirely effective. The indication is that the constrictions and fillings of the cavities offered considerable resistance to the flow of water beneath the dam.

FUNCTIONS OF THE GEOLOGIC STAFF.

Two geological surveys were made preliminary to the correction program. These served to outline the problem and establish a geologic section which was used for correlation purposes in the early stages of the work.

During the construction period, the geologists recorded the lithology, structure, weathering, and cavitation of all core recovered at Hales Bar Dam. This information was typewritten on especially prepared forms and was shown graphically on cross-sections drawn to the scale one inch to five feet. From these sections, structure and cavitation could be interpreted, predicted, and, as the work progressed, the caves could be outlined in some detail.

This information was used by the engineering and construction staffs in determining the treatment to be used, and the causes of difficulties which arose from time to time.

ACKNOWLEDGMENTS.

The leakage correction program as carried out by the Tennessee Valley Authority was conceived and directed by L. A. Schmidt, Jr., Acting Con-

struction Engineer. The construction forces were under the supervision of H. D. Towers, Assistant Construction Superintendent, while the engineering staff was directed by A. H. Weber, Engineer.

C. B. McGavock, Jr., was resident geologist from the beginning of the work until January, 1942, at which time he was succeeded by the writer who remained until completion of the work in July, 1944. Thomas M. West assisted Mr. McGavock for several months in 1941 as did the writer from September, 1941, until January, 1942. The writer was assisted by Austin Day Brixey, Jr., from January until September, 1942. All geology work was under the direction of Berlen C. Moneymaker, Chief Geologist.

U. S. BUREAU OF RECLAMATION,
VISALIA, CALIFORNIA.
Feb. 18, 1946.

REFERENCES.

1. Burd, E. M., Present conditions and possible improvements to the Hales Bar Hydro Plant, Stevens and Wood, Inc., July 17, 1929.
2. Butts, Charles, Geology of Alabama, Special Report No. 14, Alabama Geological Survey, 1926.
3. Christians, George W., Asphalt grouting of Hales Bar Dam, Engineering News-Record, vol. 96, pp. 798–802, May 20, 1926.
4. Crosby, W. O., Leakage under Hales Bar Dam, Tennessee Electric Power Company, January 3, 1922.
5. Crouch, A. W., Hales Bar Hydro Station leakage investigation—1930–1931, Tennessee Electric Power Company, September 30, 1931.
6. Eggleston, Howard, The Chattanooga and Tennessee River Company's Plant, Engineering Record, vol. 56, pp. 621–622, December 7, 1907.
7. Engineering News, Grouting and caisson sinking for the Hales Bar Dam, November 13, 1913.
8. Engineering News, The foundation difficulties at Hales Bar Dam, November 20, 1913.
9. Engineering Record, The hydraulic plant of the Chattanooga and Tennessee River Power Company, November 4, 1905.
10. Engineering Record, The Tennessee River power development at Hales Bar, vol. 59, pp. 470–473, April 3, 1909.
11. Fox, Portland P., Rate of solution of some limestone boulders in the Tennessee River, Jour. Tenn.-Acad. Sci., vol. 16, No. 4, pp. 333–335, 1941.
12. Freeman, John R., Leakage under Hales Bar Dam, Tennessee Electric Power Company, December, 1921.
13. Frink, John W., Solution of limestone beneath Hales Bar Dam, Journal of Geology, pp. 137–139, March, 1945.
14. Frink, John W., An interesting Mississippian breccia, Sedimentary Petrology, pp. 144–146, December, 1944.
15. Leggett, F. L., Geology and Engineering, McGraw-Hill, 1939.
16. Kingman, Major Dan C., Report of the Chief of Engineers, pt. 5, pp. 2957–3007, June 30, 1900.
17. Murray, Thomas E., Improvement of the Tennessee River and power installation of the Chattanooga and Tennessee River Power Company at Hales Bar Dam, Trans. Am. Soc. Mech. Eng., May, 1906.
18. Schmidt, L. A., Jr., Flowing water in underground channels, Hales Bar Dam, Tennessee, Proceedings Am. Soc. Civil Eng., pp. 1417–1446, November, 1943.
19. Smith, E. A., Report on Cahaba coal field, Alabama Geological Survey, pp. 155–157, 1890.
20. Switzer, J. A., The power development at Hales Bar, The Resources of Tennessee, vol. 2, No. 3, March, 1912.

THE QUARTZ CRYSTAL DEPOSITS OF WESTERN ARKANSAS[1]

A. E. J. ENGEL.

ABSTRACT.

Extensive geological investigations of domestic deposits of quartz crystals were undertaken by the Geological Survey of the United States Department of the Interior in the fall of 1942 in response to the urgent demand for crystals for war purposes. The work was continued throughout 1943 and took survey geologists into some 20 states in which over 1,400 deposits or reports of deposits were examined. Of the numerous highly varied occurrences of quartz examined, only the deposits in western Arkansas, in the Piedmont and Blue Ridge provinces of Virginia, North Carolina and Georgia and the placer quartz of Mokelumne Hill, California, were of sufficient promise to warrant detailed work. Production in 1943 from these areas totaled slightly less than 4 tons of oscillator quartz, over 85 per cent of which came from Arkansas.

The Arkansas deposits occur throughout the thick, deformed Paleozoic shales, sandstones, and cherts exposed along the central belt of the Ouachita Mountains. Steeply dipping fractures closely related to the major folds control the deposition of most quartz.

Clear quartz is confined largely to the terminal parts of primary crystals, which have developed without disturbance or interference, are commonly elongate parallel to their C axes and are bounded by relatively simple forms. Deposition of silica during and subsequent to the fracturing of crystals resulted in the formation of complex crystals which are characterized by extensive optical twinning and lineage structures, and commonly are bounded by aggregates of the simpler crystal forms. The principal defects in all types of crystals are twinning, smokiness, cavities, solid inclusions and fractures.

The Arkansas quartz deposits include veins, sheeted zones and stockworks. They are largely cavity fillings, apparently deposited by rising, attenuated, hydrothermal solutions, at relatively low temperatures and pressures. Minerals associated with the quartz, which constitutes 90 per cent or more of the cavity fillings, include dickite and carbonaceous material, calcite, adularia, and chlorite. The constituents of the cavity fillings could have been derived principally from magmatic sources or more probably from underlying rocks, with small additions from the rocks enclosing the cavities. The complex vein fabrics apparently resulting from intermittent regional deformation during the deposition of the quartz, and certain structural relations of the deposits, indicate that they were formed in the final stages of the Ouachita orogeny, probably in mid-Pennsylvanian time.

INTRODUCTION.

In response to the urgent demand for oscillator quartz for War purposes the Geological Survey undertook, in late 1942, a systematic search for quartz crystal deposits within the United States. No deposits were found of sufficient size and grade to offer much hope that the United States can do more than augment in a very minor way its wartime demand for this commodity.

[1] Published by the permission of the Director, U. S. Geological Survey.

Small quantities of quartz of usable quality were found in such localities as the Salmon River District, Idaho, the Piedmont and Blue Ridge provinces of Virginia, North Carolina and Georgia, and a few hundred pounds of quartz were recovered from the buried placer deposits of Mokelumne Hill, Caleveras County, California.[2] Approximately 7,000 pounds of usable crystals, more than 85 per cent of the domestic oscillator quartz production, were obtained from the quartz deposits of western Arkansas (Table I). The Arkansas deposits, with which this paper is concerned, offer a source of perhaps 125 tons of grades 1, 2, and 3 quartz, which, though small in terms of wartime demands, constitute by far the greatest potential domestic resources of this commodity known to date.

TABLE I.

WASTE ROCK, TOTAL CRYSTALS, PRODUCTION AND VALUES OF THE OSCILLATOR AND OPTICAL GRADES OF QUARTZ FROM THE MORE PRODUCTIVE MINES IN THE ARKANSAS QUARTZ DISTRICT IN 1943

Mine or prospect	Total ground moved in operations	Total crystals mined	Total oscillator and optical grades of quartz mined	Value of oscillator and optical grades of quartz mined
Blocker lead	9,000 cu. yds.	100,000 lbs.	2,100 lbs.	$10,185.00
Diamond drill, Carbon Co. No. 4	9,100 cu. yds.	16,000 lbs.	760 lbs.	4,400.00
Miller Mountain	3,260 cu. yds.	18,000 lbs.	994 lbs.	1,760.00
McEarls	1,850 cu. yds.	6,700 lbs.	134 lbs.	282.00
Fisher Mountain	16,000 cu. yds.	30,000 lbs.	206 lbs.	407.59
Diamond drill, Carbon Co. No. 5	10,000 cu. yds.	22,000 lbs.	560 lbs.	1,575.00

Previous studies of the quartz crystal deposits of Arkansas have been principally made by H. D. Miser,[3] under whose guidance the present investigation was carried on, and to whom the writer is greatly indebted for advice and kindly criticism in every stage of the work. Ralph Wilpolt worked ably with the writer throughout much of the field investigation and John Albers and E. Wm. Heinrich gave valuable field assistance in the spring of 1943. Thanks are due also to H. M. Bannerman for valuable discussion and for critical review of manuscript.

The crystal-bearing quartz deposits of western Arkansas occur in the central part of a province of genetically related quartz deposits, which are exposed in the Ouachita Mountains from Little Rock, Arkansas, west-southwest to McCurtain County, Oklahoma.[4]

Over 1,000 Arkansas crystal deposits have been examined. The more important deposits comprise a district approximately 60 miles long and 15 to 18 miles wide in the Ouachita Mountains, extending from the vicinity of

[2] Durrell, Cordell, Geology of the quartz crystal mines near Mokelumne Hill, California. In press.

[3] Miser, H. D., Quartz veins in the Ouachita Mountains of Arkansas and Oklahoma (their relations to structure, metamorphism and metalliferous deposits). ECON. GEOL., vol. 38, pp. 91–118, 1943.

[4] Miser, H. D., Quartz veins in the Ouachita Mountains of Arkansas and Oklahoma (their relations to structure, metamorphism and metalliferous deposits). ECON. GEOL., vol. 38, p. 94, 1943.

Paron, in Saline County, west southwest to Mt. Ida, in Montgomery County, Arkansas (Fig. 1). The deposits are principally cavity fillings—veins, vein zones, sheeted zones and stockworks; locally replacement of wall rock and conversion of quartzose areas of it to vein quartz have resulted in composite veins.

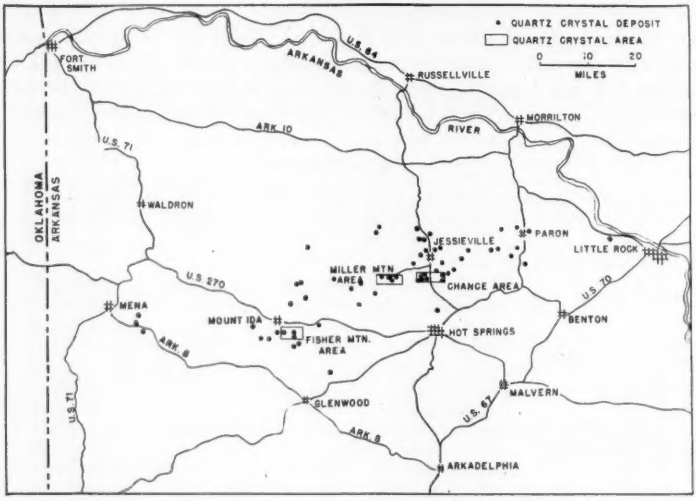

FIGURE 1. QUARTZ CRYSTAL DEPOSITS AND AREAS IN WESTERN ARKANSAS

GENERAL GEOLOGY OF THE ARKANSAS QUARTZ CRYSTAL DISTRICT.

The Ouachita Mountains, which embrace the quartz crystal district, are a chain of closely folded mountains, which as a whole is an anticlinorium of late Paleozoic age. The rocks enclosing the quartz deposits are complexly folded Paleozoic sediments, principally shales, sandstones and cherts, cut by relatively few faults. They include four competent units, three of sandstone and one of chert, separated by thick, incompetent shale masses. The shales comprise about three-fifths of the total rock section which has an aggregate thickness of over 25,000 feet.[5]

All sediments show the effects of low-grade regional metamorphism which accompanied the Ouachita deformation. Sandstones and cherts are partly recrystallized and the argillaceous rocks show various stages of conversion into slates. In general, the older, more deeply buried rocks were more affected than the younger formations.

The broad structural features of the district are best revealed by the more competent sandstones and cherts, which are compressed into tight, pitching folds that strike slightly north of east or south of east, and commonly are

[5] Miser, H. D., Structure of the Ouachita Mountains of Oklahoma and Arkansas. Okla. Geol. Survey, Bull. 50, p. 7, 1929. Miser, H. D., and Purdue, A. H., Geology of the Dequeen and Caddo Gap quadrangle, Arkansas. U. S. Geol. Survey, Bull. 808, Plate 4, 1929.

FIGURE 2. GEOLOGIC MAP AND SECTIONS OF THE FISHER MOUNTAIN AREA, MONTGOMERY COUNTY, ARKANSAS

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overturned to the south (Figs. 2, 3, 4). The thick, intercalated shales are intensely crumpled and sheared, and an obscure to moderately defined slaty cleavage is widely developed. Except near the hard sandstones and cherts the cleavage commonly cuts across the beds, generally dipping less steeply than the bedding. Faults of appreciable magnitude are comparatively rare in the district, despite the severe folding. Several faults of slight displace-

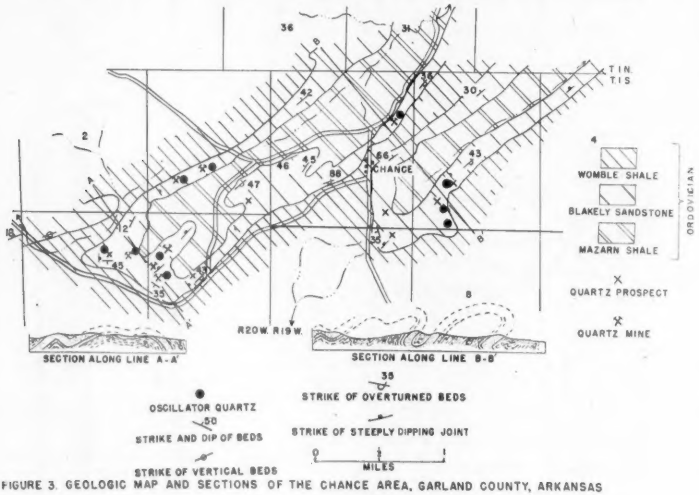

FIGURE 3. GEOLOGIC MAP AND SECTIONS OF THE CHANCE AREA, GARLAND COUNTY, ARKANSAS

ment occur in or near a few of the quartz deposits mapped but these breaks seem to have exerted little or no control on quartz deposition.

RELATION OF CRYSTAL DEPOSITS TO STRUCTURE.

The major quartz crystal deposits are restricted to groups and systems of open fractures, most of which are closely related to the regional folds. Over 85 per cent of the crystal deposits occupy steeply dipping or vertical, longitudinal fractures, which parallel or diverge very slightly from the strikes of fold axes. Thus from Mena to East Jessiveville, where the rocks are tightly compressed into eastward striking folds, the dominant crystal deposits are in east-west veins and sheeted zones. And in the Paron area where folds strike southeastward, the veins also strike southeastward.

Most of the other productive crystal deposits are partial fillings in nearly vertical, transverse fractures, that strike approximately at right angles to the axes of folds. In general, the fractures paralleling fold axes occur in all the types of rocks exposed, but they are most conspicuous and persistent along the crests of anticlines in sandstones; the mineralized transverse fissures are almost invariably limited to the flanks of folds in sandstone. Locally, as in the Chance area (Fig. 3) both sets are well developed.

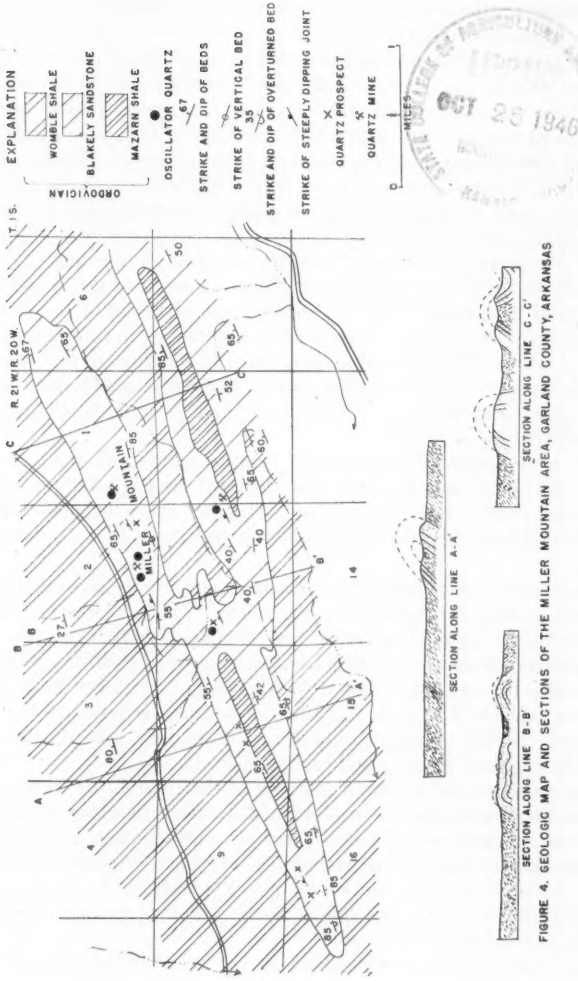

FIGURE 4. GEOLOGIC MAP AND SECTIONS OF THE MILLER MOUNTAIN AREA, GARLAND COUNTY, ARKANSAS

Rarely, as in the Crystal Mountains and elsewhere, groups of nearly parallel, steeply dipping fractures containing quartz crystal-bearing veins, diverge in strike as much as 40 degrees from the strike of fold axes (Fig. 2). Also a few widely scattered stockworks, composed of randomly oriented fractures, contain productive crystal deposits.

The general accordance of mineralized fractures and major fold axes persists not only in the quartz crystal district but throughout the major quartz deposits in Arkansas and in Oklahoma.[6] The greatest volume of quartz fills longitudinal fissures in a belt which coincides with, and extends somewhat north of, the major axis of the Ouachita anticlinorium. Although movements along these fissures appear to have been slight, the relatively great width of the veins, their compound fillings, and the included crystal pockets indicate that fissure openings persisted and were probably enlarged throughout the period of quartz deposition. Near the margins of the quartz crystal belt, especially in the Chance and Miller Mountain areas (Figs. 3 and 4), and in the Crystal Mountains (Fig. 2), where some of the most productive crystal deposits occur, the quartz crystal bearing fissures are in competent beds on the crests of folds. Many crystal pockets occur in fractures in sandstone adjacent to shale contacts and along thin, brittle sandstones interbedded with shales. Slates and shales adjacent to these competent beds, although fractured, are relatively tight and barren.

Miser [7] suggested that the quartz bearing fissures were the result of tensional fracturing caused by the final regional arching of the Ouachita anticlinorium in mid-Pennsylvanian time. Honess [8] also concluded that the major fissures in Oklahoma which controlled quartz deposition originated through tension.

The central quartz belt in the Ouachitas appears to have been the focus of tensional arching throughout the mineralizing epoch. However, the uniform relationship to regional structure and relatively sharp definition which are characteristic of most longitudinal fractures seem to indicate an initial genetic relationship between fracturing and earlier stages in geosynclinal deformation. It seems possible that these fractures formed as the result of high confining pressures [9] during severe orogenesis and were then dilated and further enlarged by regional warping and release of load.

The northern and southern margins of the crystal district appear to outline the lateral extent of the well-defined tensional fissuring in the Ouachitas. The fractures and sheeted zones which diverge as much as 40 degrees from the fold axes in the Crystal Mountains may have originated as compressive shears, induced by a locally superimposed couple or by torsion. It seems probable, however, that subsequent tension, due to flexing along the crests of folds, opened these fractures.

The transverse fractures, which strike approximately at right angles to

[6] Honess, C. W., Geology of the southern Ouachita Mountains of Oklahoma. Oklahoma Geol. Survey Bull. 32, Plate I, 1923.

[7] Miser, H. D., op. cit., p. 101, 1943.

[8] Honess, D. E., op. cit., part 2, p. 41, 1923.

[9] Bridgman, P. W., Reflections on rupture. Jour. Applied Physics, vol. 9, pp. 527–528, 1938.

the fold axes, have the typical relations of cross joints.[10] A tensional origin has been suggested [11] for joints of this type although the tension may be developed as a response to associated shearing forces.[12]

An alternative interpretation is possible for the transverse fractures that occur with the diverging fractures in the Crystal Mountains. If the diverging fractures originated as compressive shears induced by couple, the transverse fractures may represent complementary shears.[13]

QUARTZ CRYSTALS.

Quartz crystals in Arkansas deposits may be arbitrarily grouped into two general types, primary [14] and complex.[15]

Primary Crystals.—Primary crystal forms are relatively simple and uniform throughout the district (Fig. 5). All six faces of the unit prism *m*

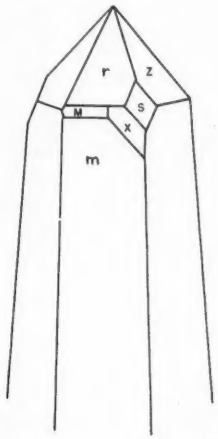

FIGURE 5. IDEAL PRIMARY CRYSTAL SHOWING THE COMMON FORMS IN THE ARKANSAS DISTRICT

(10$\bar{1}$0) are invariably present. The prisms are singly terminated by the positive rhombohedron *r* (10$\bar{1}$1) and the negative rhombohedron *z* (01$\bar{1}$1). Additional forms include the right (11$\bar{2}$1) or the left (2$\bar{1}\bar{1}$1) trigonal pyra-

[10] Closs, Ernst, The Application of Recent Structural Methods in the Interpretation of the Crystalline Rocks of Maryland. Johns-Hopkins Press, Baltimore, Md., pp. 74–75, 1937.

[11] Closs, Ernst, op. cit., p. 74, 1937.

[12] Griggs, David, Deformation of rocks under high confining pressures. Jour. of Geology, vol. 44, pp. 552–554, 1936.

[13] Mead, W. J., Notes on the mechanics of geologic structures. Jour. of Geol., vol. 28, pp. 505–623, 1920.

[14] The term primary as used in this paper refers to crystals that have remained in the same position during their entire growth.

[15] Complex crystals show evidence of a complex development involving breakage and movement during growth.

mids, *s*, less commonly the right $(5\bar{1}61)$ or left $(6\bar{1}\bar{5}1)$ positive trapezohedron *x* and a steeper rhombohedron $(30\bar{3}1)$ M (Fig. 7).

Complex Crystals.—Although the shape and habit of the primary crystals are mostly quite simple, recurrent breakage and regrowth have resulted in variously shaped complex crystals. The portions formed subsequent to breakage are characterized by widespread optical twinning and lineage structures,[16] and are bounded by aggregations of the simple crystal faces. Miser[17] remarked that:

> Many stages in the further growth of fractured crystals may be noted. These range from fractured surfaces in which little quartz has been added to surfaces that are nearly or completely obliterated by further growth. The new growth on such surfaces has the same crystallographic orientation as that of the original crystal. Some have been bent into curved shapes through fracturing and subsequent healing of the fractures by new quartz. Crystals displaying all the features just enumerated have been observed at many localities in western Arkansas.

Most breaking during growth of candle crystals evidentally occurred in that part of the crystal which at the time of deformation contained the most imperfections. Since this was commonly at the base of the crystal, the initial elongate shapes of many crystals were retained after breakage. Commonly the break occurs parallel to *r* or less often *z*, or along irregular surfaces making small angles to the basal plane. Under relatively slight deformation these crystals may suffer little other alteration to their external form, although internal imperfections such as tiny cracks or veils are exaggerated and introduced. With subsequent growth the broken crystals tend to develop a second termination and most doubly terminated crystals in the Arkansas district probably originated in this fashion. The new faces developed on breaks tend to be the common forms whose planes are nearest that of the break. Thus, when a crystal fractures along a plane parallel to *r* or *z*, which is especially common, the new termination consists of the most concordant rhombohedral face, greatly developed, and five incipient ones. With continued additions of silica the incipient rhombohedral faces enlarge, and the initially large face diminishes in size. These terminations are opposite the tapered end of the crystal and may thus be distinguished from primary terminations distorted by growth in solution currents. They are further characterized by an abnormal development of vicinal faces. Where the original break is very irregular, secondary growth is especially likely to be established at numerous independent centers of nucleation which enlarge into lineage groups bounded by aggregates of appropriate faces. This produces prisms terminated at one end by the original 6 rhombohedral faces and at the other end by a multitude of the simple crystal forms.

Defects.—Over 80 per cent of the Arkansas oscillator quartz crystals mined in 1943 were graded and priced according to the classification of the National Bureau of Standards. In general these specifications require that quartz cut

[16] Burger, M. J., The lineage structure of crystals. Zeitschr. Kristallographie, Band 89, pp. 159–220, 1934.

[17] Miser, H. D., Quartz veins in the Ouachita Mountains of Arkansas and Oklahoma (their relation to structure, metamorphism and metalliferous deposits). Econ. Geol., vol. 38, p. 99, 1943.

into oscillator plates must be essentially free from most imperfections, including twinning. The more common defects of quarts as they occur in the Arkansas quartz crystals include: smokiness, cavities, inclusions, fractures, cleavages and twinning.

Smoky coloration in Arkansas crystals, ranging from an almost imperceptible tint, which usually imparts a faint oily sheen to the crystal, to shades of deep brown or almost black, is relatively common. Variations in the degree of smokiness are apparent within single crystals, commonly in zonal growths that grade into colorless or milky quartz toward the base of the crystal. Anhedral to subhedral vein quartz is never smoky. Rarely, the smoky quartz is pleochroic. Smoky crystals are commonly confined to particular veins in a deposit, or to one or more pockets in a vein filled mostly with colorless crystals.

Cavities or vacuoles within crystals and vein quartz constitute one of the commonest imperfections in Arkansas quartz crystals. The general types in the order of their abundance are (1) highly irregular cavities, (2) tubular or needle-shaped cavities, and (3) negative and skeleton crystals. These types are arbitrarily defined, often vary widely in size, and a few cavities show features of more than one type. Most cavities in vein quartz and crystals probably were formed contemporaneously with the deposition of the quartz surrounding them, but some of the smaller tubular cavities may have resulted from exsolution, and many chains of cavities, tubular cavities and negative crystals may have been formed by solution.[18]

Some chains of cavities cross grain boundaries without offset, and were probably formed after the enveloping quartz.[19] Some crystals contain cavities that are partially filled with water (called water crystals in the district). These may be solution forms [20] or more probably examples of skeletal crystal growth. [21, 22] Slight natural solvent action seems indicated on some crystals by natural etch pits within the cavities and on various crystal faces.

Solid inclusions in crystals and grains consist chiefly of carbonaceous material, sand, clayey aggregates and associated vein minerals. Brookite blades are partly enclosed in several crystals mined at Miller Mountain. Many inclusions especially of associated minerals are aligned along crystallographic directions and seem to be contemporaneous with the enclosing quartz; others, localized along veins and flaws, probably were introduced by solutions subsequent to the deposition of the quartz.

Fractures are more abundant in Arkansas quartz than are obvious cleavages and partings and are found in the basal portions of all crystals. Fractures may occur singly, but commonly short, intersecting or branching conchoidal to irregular fractures form numerous compound breaks in the quartz.

[18] Judd, John W., On the relations between the solution planes of crystals and those of secondary twinning and on the development of negative crystals along the former. Mineralog. Mag., vol. 7, pp. 82–92, 1886.

[19] Ferguson, H. G., and Gannett, R. W., Gold quartz veins of the Alleghany district, California. U. S. Geol. Survey Prof. Paper 172, pp. 41–44.

[20] Judd, John W., op. cit., pp. 81–92, 1886.

[21] Bain, G. W., Skeleton quartz crystals. Amer. Mineralogist, vol. 10, 1925.

[22] Sosman, R. B., The Properties of Silica: pp. 513–514, The Chemical Catalog Co., Inc., New York, 1927.

Compound fractures having uniform overall trends parallel to crystal faces may resemble cleavages.

Many breaks in the Arkansas quartz crystals are parallel to the structural planes in the crystal lattice that offer the best possibilities for cleavage.[23] Cleavage parallel to *r*, or less commonly *z*, is the most common. Approximately one-fourth of the crystals in many localities have an *r* or *z* cleavage clearly developed and most crystals can be readily cleaved along the *r* plane.

Optical twinning (Brazil twin, Chrial type) is present to various degrees in quartz from all the tested localities, and the common form of electrical twinning (Dauphine, orientational type), although seemingly less abundant at many deposits is locally intensely developed. The Japanese twin (twinning plane $11\bar{2}2$) is extremely rare. Of the four specimens from the district that show twinning of the Japanese type, three are known to have come from Fisher Mountain, and the other one may have.

The proportions of "eye clear" quartz (clear to the unaided eye) that is more than 60 per cent optically twinned as compared to eye clear quartz less than 60 per cent optically twinned from six of the larger producing mines or areas are given below.

Locality	Percentage by weight of eye clear quartz > 60% optically twinned	Percentage by weight of eye clear quartz < 60% optically twinned	Weight of eye clear specimens examined	Number of eye clear specimens examined
Fisher Mountain	45	55	50 lbs.	125
Miller Mountain	77	23	225 lbs.	500
McEarls	28	72	21 lbs.	50
Blocker lead	86	14	1,300 lbs.	800
Shaw area	23	77	40 lbs.	100
Beaudry area	85	15	100 lbs.	150

Although attempts to correlate the occurrence and nature of optical twinning in Arkansas quartz with the geologic features of the deposits must be highly speculative because of the meager information available it is known that the ratio of highly twinned to relatively untwinned quartz varies widely between localities in dissimilar country rocks, but is commonly fairly constant within a single deposit or group of several closely related deposits.

Electrical (Dauphine) twins were recognized in the district by the writer from surface inspection of forms, and checked by etching. In numerous localities the contrasting sheen of interpenetrating *r* and *z* faces may be related to sutures on *m*, as found on the ideal electrical twins, and in a few instances vicinal faces[24] somewhat similar to Kalb's type I are present. These criteria are not widely applicable because (1) identical sutures on *m* may be due to parallel crystal growth, (2) conclusions made from vicinal faces are not always reliable, and (3) the luster of the positive and negative rhombohedral faces may be similar prior to etching.

[23] Fairbairn, H. W., Correlation of quartz deformation and its crystal structure. Amer. Mineralogist, vol. 24, pp. 359–364, 1939.

[24] Kalb, Georg, Beiträge zur Kristallmorphologie des Quarzes. Zeitschr. Kristallographie, Band 86, pp. 439–452, 1933.

FORM, SIZE AND DISTRIBUTION OF QUARTZ CRYSTAL DEPOSITS.

The quartz crystal deposits include single veins, systems or groups of veins, sheeted zones, stockworks and various combinations of these. Simple quartz-filled fissures in sandstones and cherts may merge into fracture systems containing much broken country rock. These fracture systems in turn may widen or merge into sheeted zones of closely spaced, nearly parallel fractures, locally complicated by cross joints or brecciation. Most deposits enclosed in slates and shales are relatively simple veins and subparallel or aligned groups of veins.

Single veins generally have abrupt bulges and equally abrupt thinnings or terminations. A veinlet of quartz, a fraction of an inch or several inches wide, may swell into an irregularly rounded or lenslike pocket or vein mass one to four feet wide, within a few feet along the strike. Slabby and irregular wall-rock inclusions are widespread along a few veins and are present locally in others.

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FIG. 6. A group of quartz crystals from one of the larger vein zones in the Chance area. Crystals of this size are usually milky throughout, although "eye clear" portions weighing as much as 19 pounds have been cobbed from some of them. Pick is thirteen inches long.

Groups of veins, composed of single veins in subparallel, intersecting fractures, predominate throughout the district. The groups are characterized by slightly diverging fractures, which break the country rock into a series of lenticular or irregular slabs or ribbons. Fracture groups in the argillaceous rocks are usually characterized by a greater ratio in length to width of quartz filling than those in sandstones.

Groups of veins enclosed in all types of rocks frequently occur in subparallel or aligned systems, either with single veins or with other vein zones. Various transitions between single veins and vein zones also occur throughout the crystal district.

Parts of numerous deposits in quartzites of the Crystal Mountains are in sheeted zones. The sheeted fissures are commonly a few inches to 2 feet apart and segment the country rock into flat slabs, lenses and wedge-shaped fragments. Most fissures are thinly coated with quartz or "healed" by veinlets less than 6 inches wide, which are frozen to both walls. Locally, however, the introduced silica exceeds in volume the partitioning sheets and slabs of wall rock. Fracture systems in the quartzitic sandstones of the Fisher Mountain and Chance areas are further complicated by superimposed, randomly oriented fractures and shears. Crystal bearing stockworks are thus formed by veinlets and irregular masses of quartz that fill cavities and cement the irregularly fractured country rock, often with transverse or longitudinal veins which dip steeply.

Textures.—A wide range of textures is present in the quartz deposits. Grouped in the order of their abundance the chief primary textures are : (1) massive, milky, subhedral to granular coarsely crystalline quartz; (2) anhedral to euhedral, milky comb quartz; (3) partially clear or milky crystals in vugs or pockets.

All gradations may be found between these arbitrarily defined textures in a single fissure filling. Massive, milky, anhedral quartz is traceable into tight comb quartz, which opens into vugs or pockets where available space permitted the partial development of crystal faces.

Massive, milky quartz ranging in grain size from microscopic dimensions to at least 3 feet in the largest dimension, predominates in most deposits. Microcrystalline aggregates are extremely rare. The grain size ordinarily is proportional to the width of any single vein segment, but there are numerous exceptions.

Comb quartz is the predominant texture in most partially filled fissures, in narrow vein fillings, and in narrow segments of compound veins. The widest single unit of comb quartz observed measured about 3 feet. Quartz fillings in excess of 12 inches thick commonly contain irregular areas of randomly oriented grains. In most of these wider, unsegmented cavity fillings the comb structure constitutes only a small part of the cavity filling. Nearly parallel, sheetlike, or lense-shaped combs of various widths, partially separated by ribbons of shale, carbonaceous quartz, or areas of massive quartz, are found in some compound veins.

The term "pocket" is applied to all types of vugs and crystal-bearing cavities, which result from incomplete or imperfect fissure filling.

Comb pockets, lined by opposed crystals oriented approximately normal to the vein walls, are the commonest type of primary pocket (Fig. 7).

Distortion of crystal growth is typically shown in such pockets by an abnormal development of one, or as commonly two or three, adjacent rhombohedrons on the crystal, so that the terminal apex is asymmetrically oriented. In over three-fourths of the crystal forms showing distorted growth the apex

is on the upper [25] side of the crystal and the enlarged rhombohedral faces are on the downward side of the crystal in the veins. Successive growth zones are clearly shown in the Arkansas crystals by "phantom" inclusions and by

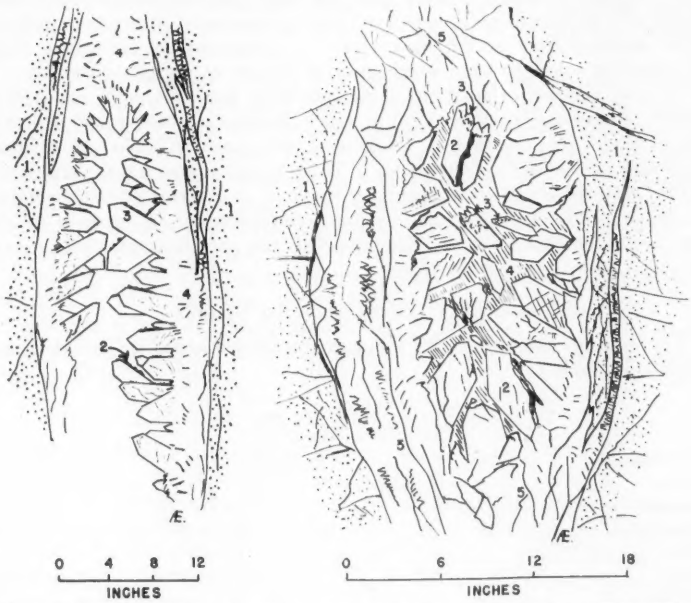

FIG. 7 (left). Section of comb crystal pocket in a quartz vein at Fisher Mountain. Distended rhombohedral faces are on the downward side of most crystals. Incrustations occur on the upper sides of crystal. Clear quartz is principally at the terminal ends of the less confined crystals. Remaining space around crystals is usually filled with tightly packed, halloysitic red clay.

1. Crystal Mountain sandstone.
2. Crustification on crystals.
3. Clear quartz.
4. Milky vein quartz.

FIG. 8 (right). Slightly deformed quartz crystal pocket in a vein of sandstone.

1. Deeply weathered argillaceous Blakely sandstone.
2. Ruptured quartz crystal.
3. Part of crystal grown subsequent to rupture.
4. Red clay filling in crystal pocket.
5. Massive, milky vein quartz.

smoky bands. Typical growth distorted Arkansas crystals in which successive growth zones were especially visible were sectioned by the writer. Sections cut parallel to the c (z) axis in a vertical plane indicate that the greatest

[25] Bandy, Mark C., Discussion, direction of flow of mineralizing solutions. ECON. GEOL., vol. 32, p. 330, 1942.

deposition of silica and the most rapid growth of crystals have been on the downward side of crystals and on the enlarged rhombohedral faces. These data are in opposition to the conclusions of Newhouse [26] who stated that the most abundant additions of silica occurred largely on the small *r* and *z* faces. Along with additional independent evidence presented in this paper, the evidence obtained from sectioning crystals is interpreted as indicating rising silica bearing solutions from which most of the quartz crystals grew.

A more random orientation of the quartz in larger veins is manifest in pockets of irregular, rounded form in which the component crystals project at various angles into the cavity. Because of their random fabric and sackform shape they are called "sack pockets." There exists almost a complete transition between these and comb pockets. Random or diverse crystal orientation is commonly apparent where the feeding solutions were not confined to uniform, restricted channelways. These pockets are therefore more common in the wider veins, especially in shales.

MINERALS ASSOCIATED WITH QUARTZ.

The minerals associated with the quartz are listed and their paragenesis is indicated in Table II.

TABLE II.

ASSOCIATED MINERALS.

Mineral	Hypogene								Supergene		
Azurite									—	—	—
Limonite									–	–	–
Malachite									—	—	—
Wad									–	–	–
Kaolin									–	–	–
Quartz	—	—	—	—	—	—	—	—	—	—	—
Chlorite	—	—	—	—	—	—	—	—			
Calcite	—	—	—	—	—	—	—	—	—	—	—
Carbonates $CaO(FeMn)OCO_2$	—	—		—	—	—	—	—			
Adularia	—	—	—	—	—	—	—	—			
Rectorite			—	—	—	—	—	—			
Dickite			—	—	—	—	—	—			
Siderite			—	—	—	—	—	—			
Pyrite				—		—		—			
Sphalerite					—	—		—			
Galena						—		—			
Chalcopyrite				—		—		—			

Adularia is a component of many deposits in shale, and is sparingly present in several fissure fillings in argillaceous sandstone. At very few places, crystal pockets in veins in shale are lined with adularia crystals as much as half an inch across, and adularia may be included in the quartz crystals. More commonly adularia is intergrown with massive vein quartz, particularly along the margins of veins adjacent to the argillaceous wall rock.

[26] Newhouse, W. H., The direction of flow of mineralizing solutions. ECON. GEOL., vol. 36, pp. 618–619, 1941.

Lamellar, rhombohedral, and massive vein calcite, or more commonly cavities indicating the former presence of calcite occur in many deposits. Calcite is a relatively abundant vein constituent in carbonate-bearing sediments and is scarce or absent in the carbonate-free environments. Lamellar calcite, or molds thereof, occur principally in quartz deposits in the Bigfork chert and upper part of the Womble shale.

Pale-to-medium green chlorite is a relatively common constituent of the quartz veins in the Stanley shale and is rarely present in veins enclosed in other shales. Vermicular and granular aggregates of chlorite form phantoms and irregularly shaped inclusions in crystals and in masses of the vein quartz.

Dickite is widely distributed as coarsely crystalline (up to 1.5 mm.) or fine-grained aggregates in quartz crystal pockets and as veinlets coating fissures in massive quartz. It forms inclusions in quartz crystals, especially in deposits located along the margins of the district.

Rectorite [27] occurs with quartz in the Jackfork sandstone, especially near Angling and Smith pinnacles, along the Saline-Garland County line. The two minerals usually occur together in highly deformed veins. The quartz commonly shows ragged, irregular contacts with the rectorite folia and is partly enveloped in them.

WALL ROCK ALTERATION AND REPLACEMENT.

Most of the rocks enclosing the quartz deposits show only slight alteration or replacement by the mineralizing processes.

In the more porous sandstones, cherts, and siltstones, however, many of the component grains along fissures have been partly corroded by the encroaching solutions. Partial solution, especially of the finer fractions in the sandstones and cherts, has been sufficient to leave only skeletal grain aggregates at some localities.

Some veins in cherts and sandstones are slightly enlarged as a result of recrystallization of narrow selvages of wall rock. In most localities the actual volume of siliceous wall rock converted into vein matter by recrystallization is less than one-tenth the total volume of the vein. Locally, however, solutions have introduced silica into large, porous aggregates of sandstone or chert adjacent to fissures. Various stages in the process of conversion of this wall rock to vein quartz and crystals may be seen, ranging from slight silicification of the wall rock to the envelopment of host rock quartz grains which then coalesce with the introduced silica and assume a common crystallographic orientation with it. The "sand crystals" so formed are commonest in deposits near Chance.

Recrystallization of the sandstone wall rock is responsible for a considerable volume of the vein quartz and crystals at a few deposits in sandstones and for appreciable parts of small veinlets in many siliceous rocks. Even in areas of greatest recrystallization, however, the local supply of quartz has been augmented by silica introduced by the solutions.

Alteration of shales and slates is confined largely to thin fragments or

[27] Brackett, R. N., and Williams, J. F., Newtonite and rectorite—two new minerals of the kaolinite group. Am. Jour. Science, vol. 142, pp. 16–21, 1891.

finely broken aggregates within the mineralized fissures and to narrow bands of host rock along fissure walls. Locally the silica-bearing solutions permeated the more porous fragments and either partly recrystallized or silicified them. In other deposits the more exposed argillaceous materials were soaked by the solutions which leached large quantities of carbonaceous material and lesser amounts of potash, magnesia and perhaps some alumina. The altered fragments are pale gray to buff, halloysitic aggregates.

More rarely, exposed slaty wall rock fragments show various stages of replacement by quartz. Almost total replacement is indicated by ghost structures of slaty cleavage and bedding, which persist in narrow zones of carbonaceous and sericitic vein quartz.

Where fractures cut the slabby limestone beds which are interlayered in the shales and cherts, bands of limestone up to a few inches wide are recrystallized into coarse grained white calcite. A small amount of calcite has also been dissolved from the fractured calcareous cherts and sandstones converting them into porous, friable masses.

RELATION BETWEEN VEIN MINERALS AND TYPE OF WALL ROCK.

The difference in the physical and chemical properties of the wall rocks is well reflected in the enclosed quartz. Along the margin of the district, the quartz crystal-bearing deposits are restricted to standstones and quartzites because the greater strength and brittleness of these rocks produced open fissures during deformation whereas adjacent, softer shales remained relatively tight. In the central part of the major quartz belt open fissures were formed in argillaceous, as well as competent siliceous rocks, and the softer argillaceous walls offered a more contaminated and mechanically unstable environment for the silica-depositing solutions than did fissures in the more competent siliceous rocks. This partly accounts for the greater volume of silica found in the shales, containing only meager amounts of clear quartz.

The type of wall rock enclosing the deposits has also influenced the kinds of minerals associated with the quartz. The restriction of adularia and more locally chlorite mainly to cavity fillings in the shales seems to warrant the conclusion that the formation of these minerals was dependent upon these wall rocks as a source of potash and magnesia. Significantly, in the tuffaceous Stanley shale, which has a higher magnesia content than the other shales of the district, chlorite is especially abundant. Adularia is present in all shales, being particularly abundant in zones of the Womble. The chlorite and adularia in cavity fillings are confined chiefly to narrow areas adjacent to altered argillaceous wall rock.

The association of vein calcite and crystals with quartz deposits, principally in calcareous beds, indicates that the chemical nature of the wall rock controlled the formation of calcite in the deposits. All transitions from dark, fine grained limestone to white, coarsely crystalline vein calcite are observable along quartz veins cutting limestone, and in some brecciated or tightly fractured limestones this recrystallized wall rock may form most or all of the vein. Veins traced a few feet beyond limy beds show a marked impoverishment in calcite. The occurrence of lamellar calcite (which is supposed to be the

highest temperature form) with quartz chiefly in deposits in the Bigford chert and upper Womble shale may be largely attributable to some stratigraphic control exerted by these zones. The Bigfork and Womble are distinctive from other wall rocks in the district in that they contain chert, calcite and pyrite as abundant constituents.

SECONDARY FEATURES RELATED TO DEFORMATION.

Few quartz deposits in the district fail to show marked effects of deformation during and following the silica deposition.[28] Miser [29] in commenting on these features of the deposits says:

> Some veins in laminated sandstone have been offset by shearing along the laminae, some have been cut by faults and thus display slickensides; and some have been formed in two sets, the later one crossing the earlier one. In addition, some veins have been crushed into coarse and fine breccia in whose spaces a later generation of quartz grew. Quartz crystals by the hundreds have been noted that have been broken away from their attachment and have grown by the addition of further quartz to the fractured surfaces. In fact the crystal clusters at some places have been so greatly fractured that clusters do not remain; all the crystals at such places are doubly and singly terminated and lie loose in the clay.

Crystal pockets—the source of the clear quartz—were especially susceptible sites for breakage and subsequent deposition of silica. Those appreciably altered are here termed "crush pockets," and the various types of deformation are illustrated in their complex crystal fabrics.

Where opposing crystals were interlaced in elongate pockets and fissures, the slightest differential movements sheared the more confined crystals from their roots and "veiled" or distorted numerous others (Fig. 8). Simultaneously, new cavities and fissures were opened. The loosened or "erratic" crystals lodged in random fashion in the new fissures, where they were frozen by continued deposition of silica and surrounded by a new generation of comb quartz. In these veins most of the "erratic" crystals are milky and lie among the small, clear, later crystals in a manner similar to down timber among the second growth saplings.

Locally, crystals have been broken or successively distorted and rotated by differential movements of fissure walls until their axes lie essentially parallel to the cavity walls. Some of the fissures are clogged with aggregates of closely packed crystals which are frozen together in trachytoid and swirled patterns. A large number of individual crystals appear bent or warped, because of slight offsets along cleavages, or fractures accompanied by rehealing.

Where movements resulted in the constriction of a crystal-lined cavity, the flattened, distorted crystals lie matted in crisscross pattern. In the more severely crushed pockets, crystal fragments, brecciated vein matter, and wall rock form a porous rubble. The complex products are distorted crystal mats typified especially by some of the deposits in shales.

[28] In general the value of a deposit as a source of oscillator and optical quartz is in inverse proportion to the severity of deformation, though, paradoxically enough, deformation and regrowth may markedly improve a deposit as a source of museum or curio specimens.

[29] Miser, H. D., op. cit., p. 99, 1943.

In veins where extensive deformation has occurred during crystal formation, minute chips of vein quartz or wall-rock are piled sometimes to the angle of repose on the *upper* [30] side of the crystals. Many of the encrusting fragments are only slightly modified or enlarged and can be traced to their source in the crushed fillings above. Similarly, most encrustations, so prevalent on the Arkansas crystals, seem to owe their origin largely to migration by gravity of particles precipating from the solutions or loosed from superposed parts of the cavity at various stages during cavity filling, rather than to a more copious nutrition on the *stoss* or downward side of crystals as suggested by Newhouse.[31] These particles, on larger crystals, are commonly recrystallized, enlarged or enveloped by subsequent additions of silica.

ORIGIN.

The quartz crystal deposits of the district are chiefly cavity fillings formed by rising, attenuated, hydrothermal solutions probably at depths and temperatures approximately the upper mesothermal and lower epithermal zones of Lindgren. The relatively widespread crystal perfection found in the district as well as the absence of colloform structure suggests that much if not all of the quartz grew molecule by molecule from a solution of perhaps alkali silicates in which quartz was the primary phase.

The efficacy of ground waters in leaching, transporting, and redepositing silica is a well known, and widely appealed to, geologic process. However, meteoric waters moving downward or laterally seem to have played an insignificant role in the cavity fillings. The association of dickite, platy calcite, and adularia, all contemporaneous with the quartz, indicates hydrothermal solutions as the agent of transport. Other features that indicate rising solution currents are—the growth distortion of many crystals within the deposits, the wide vertical range of the deposits, their lack of relations to surface features, and their persistence in the most deeply dissected rocks. Any widespread lateral movement of solutions also seems precluded by complex folding of the beds and the steepness of solution channelways.

The quartz deposits and their associated minerals were probably derived from several sources, namely—(1) a subjacent magma, (2) rocks in and adjacent to deep seated channel walls traversed by the through going solutions, and (3) wall rocks immediately adjacent to the present deposits. Thus, magmatic solutions not only transported magmatic constituents but also carried constituents from wall rocks both far from and near the cavities.

The source of the transporting solutions is presumed to be an underlying magma, although this is not supported by direct evidence. Metals, which usually characterize magmatic solutions, are sparse and may well have been lost along the extensive routes traveled by the solutions before reaching the exposed rock zones. In contrast, common constituents of rock minerals, chiefly silica, may have been added to the solutions through leaching of the rock sequence traversed.

[30] Bandy, Mark C., op. cit., p. 330, 1942.
[31] Newhouse, W. H., op. cit., p. 620, 1941.

The hydrothermal solutions ascending into the lowermost strata now exposed were saturated with respect to the minerals, quartz, dickite, calcite, and iron carbonates that were crystallizing in the cavities. They were essentially neutral, as is best indicated by the lack of evidence of wall rock corrosion, especially in the limestones.

Selective incursion of these solutions into the wall rocks adjacent to the fractures and fissures permitted the removal of chemical elements from the wall rock and their incorporation in the cavity fillings. Solutions permeating and leaching the shales and slates of the district were enriched in potash, magnesia, and possibly silica and alumina. That these introduced solutions seem to have been impoverished in potash and magnesia is demonstrated by the absence of these elements in cavity fillings in other than argillaceous host rocks. As a result a marked concentration gradient was set up in the solutions between the soaked wall rock and the cavity. It is suggested that both potash and magnesia migrated by slow, lateral diffusion outward toward the cavity with their addition to the general system resulting in the immediate formation of adularia and chlorite.

The derivation and movements of carbonaceous substances from the black shales and shale clots in sandstones into the cavity fillings are widespread. The carbonaceous material has been introduced into the quartz as fine flaky aggregates and seems to have been at least locally transported by the solutions as a colloidal fraction or as discrete particles.

Although small amounts of silica appear to have been removed from the shales and slates, the principal wall rock sources of silica were the porous sandstones and cherts. In these beds the silica from the smaller, and therefore, more soluble quartz grains seems to have been dissolved and redeposited on the relatively large quartz grains and crystals of the cavity fillings. Considerable silica seems to have been abstracted in this fashion from the wall rocks and incorporated into the cavity fillings. Siliceous wall rock is also converted to vein material by the coalescence of the grains into larger quartz individuals without appreciable migration of the silica. Even in areas of greatest solution and recrystallization, however, the local supply of quartz has been augmented by silica introduced by the solutions.

Some alumina may also have been derived from the aluminous wall rocks and converted into the dickite crystals of the cavity fillings.

Growth and continued preservation of perfect quartz in the deposits were possible for relatively few individual crystals. The initial solutions, rising toward the surface into zones of diminishing pressures and temperatures, were undoubtedly contaminated by crushed host rock and by any connate solutions that may have persisted in the sediments. This contamination probably facilitated nucleation and the deposition of silica but resulted in numerous grains and crystals clouded by various impurities and physical imperfections. As the channelways were cleansed and warmed by the ascending solutions, the system became more stabilized. The slower, more regular precipitation from relatively constant solutions in uniform circulation, enhanced the opportunities for more perfect unit crystal growth. Even then the formation of clear quartz was confined almost solely to the unstressed, terminal parts of crystals.

Pressures differentially applied to crystals as a result of their mutual interference during growth, induced physical imperfections and consequent milkiness.

Each succeeding deformation during the course of mineralization introduced hydrodynamic variations, and a contamination of the system. New cavities were formed and preexisting ones broken. During periods of instability the physico-chemical system probably varied from place to place. In general, greater opportunities for contamination of solutions, and the incorporation of impurities in the growing quartz existed in shales, limestones, and impure cherts, than in sandstones.

AGE OF THE QUARTZ DEPOSITS.

The available evidence indicates that the quartz crystal and associated mineralization took place between early Pennsylvanian and early Cretaceous time, and that it is not related to the Cretaceous igneous activity in Arkansas. That the deposits were formed during the final stages in the Ouachita orogeny is indicated by the control of quartz deposition by fractures related to the folding of the Paleozoic rocks, the recurrent deformation during formation, and the localization of the major quartz deposits in zones of great metamorphism [32] in the orogen. It is the consensus of recent workers [33] who have studied the geology of the Arkansas-Oklahoma area that the Ouachita deformation occurred in the mid-Pennsylvanian, and so a similar age appears to be indicated for the quartz crystal deposits.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Feb. 26, 1946.

[32] Miser, H. D., op. cit., pp. 102–107, 1943.

[33] Honess, C. W., Geology of the southern Ouachita Mountains of Oklahoma. Okla. Geol. Survey Bull. 32, p. 259, 1923. Morgan, G. D., Geology of the Stonewall quadrangle. Okla. Bur. Geology, Bull. 2, pp. 19–21, Norman, Okla., 1924. Powers, Sidney, Age of the folding of the Oklahoma Mountains—the Ouachita, Arbuckle, and Wichita Mountains of Oklahoma and the Llano-Burnet and Marathon uplifts of Texas. G. S. A. Bull. 39, pp. 1047–1049, 1928. Miser, H. D., Carboniferous rocks of Ouachita Mountains. A. A. P. G. Bull. 18, pp. 1007–1009, 1934. Harlton, B. H., Stratigraphy of the Bendian of the Oklahoma salient of the Ouachita Mountains. A. A. P. G. Bull. 22, pp. 861–864, 1938.

WHITE HORSE ALUNITE DEPOSIT, MARYSVALE, UTAH.

MAX E. WILLARD AND PAUL DEAN PROCTOR.[1]

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ABSTRACT.

All of the many known alunite deposits in the Marysvale region of Utah are confined to the Tertiary volcanics and more specifically to the Bullion Canyon Volcanics of early Tertiary age. The alunite in these rocks occurs both in veins and in irregular replacement bodies. The White Horse deposit, about 4½ miles northeast of Marysvale, is a replacement deposit in a calcic quartz latite of the upper part of the Bullion Canyon Volcanics. This latite flow is divided into an upper vesicular and brecciated layer and a lower more massive layer which has a clearly developed flow structure. Locally, while the flow was still in motion, the upper vesicular layer and the flow structure of the lower layer were conformably folded. In the main these folds are isoclinal, trend north, are slightly overturned to the west, and plunge gently south.

At the White Horse deposit the alunite occurs in three main ore bodies, each of which consists of several smaller bodies whose long dimensions are about parallel and trend northerly. At the surface the main bodies are roughly lenticular, several hundred feet long, and less than 100 feet wide at their widest part. For the most part they dip steeply east and plunge gently south. Surrounding each of the bodies is a thick envelope of partly kaolinized latite.

The alunite bodies are mostly restricted to the upper vesicular and brecciated layer of the latite and are most continuous and reach their greatest depth along the axial planes of the primary fold troughs. The

[1] Published by permission of the Director, Geological Survey, U. S. Department of the Interior.

infolding of the upper vesicular and brecciated layer apparently produced porous troughs of rock along which the mineralizing solution could circulate. Concentrated in these troughs, the solution was able to replace the porous rock thoroughly. Subsequent erosion has left parts of the infolded and replaced porous layer.

During the alunitization of the latite 5–10 per cent of the silica and most of the sodium, calcium, and iron were removed. The amount of aluminum and potassium was not appreciably changed. The only addition during the replacement was 15 to 23 per cent of SO_3. These data indicate that the alunite replacement was accomplished by a sulphate-bearing solution. At the deposit there is now no evident surface or near-surface source of sulphur and therefore the sulphur added during alunitization is believed to have been in part at least of magmatic origin. It is suggested that the quartz monzonite stock exposed north of the mine area may overlie the source.

INTRODUCTION.

General Statement.—For many years prospectors had known of the large veins of "pink spar" that occur in the high mountains southwest of Marysvale, Utah. Many samples of this "pink spar" were assayed for gold, but it was not until 1910 that the mineral was identified as vein alunite. The veins were immediately recognized as potential sources of potash and the increased demand for domestic sources of this material brought on by World War I resulted in the discovery not only of additional vein deposits but replacement deposits as well. The latter were first recognized at Marysvale in 1915. Before many of the replacement deposits were explored to any great extent the war stimulus was removed and, except for occasional subsequent shipments for fertilizer or experimental purposes, production and exploration ceased.

With the start of World War II, interest was revived and the alunite deposits were considered as a potential source of aluminum as well as of potash. However, the emphasis was on the replacement deposits, two of which, the White Horse and the Yellow Jacket, have been thoroughly explored and partly developed by the operating company, Kalunite, Inc. This exploration and development have revealed new geologic information supplementing that already recorded by Butler and Gale,[2] Loughlin,[3] Butler,[4] Callaghan,[5] and others.

The field work on which this paper is based was done in 1942–43 during the period of exploration and exploitation of the White Horse deposit by Kalunite, Inc. It represents a part of a field study of all known alunite deposits of consequence in the Western States undertaken and recently completed by the Geological Survey, U. S. Department of the Interior. Though the results of studies of other deposits have a bearing on the conclusions reached concerning the White Horse, this deposit is unique in that it has been explored more thoroughly than any other both on the surface and

[2] Butler, B. S., and Gale, H. S.: Alunite, a newly discovered deposit near Marysvale, Utah. U. S. Geol. Survey Bull. 511, 1912.

[3] Loughlin, G. F.: Recent alunite developments near Marysvale and Beaver, Utah. U. S. Geol. Survey Bull. 620, 1915.

[4] Butler, B. S.: Ore deposits of Utah. U. S. Geol. Survey Prof. Paper 111, 1920.

[5] Callaghan, Eugene: Preliminary report on the alunite deposits of the Marysvale region, Utah. U. S. Geol. Survey Bull. 886-D, 1937.

underground. Furthermore the stripping and quarrying of a large part of the deposit has permitted day-to-day observation of changes of all the features of the deposit both laterally and in depth. Hundreds of samples have been assayed by the company and a few critical, more complete analyses, have been made by the Geological Survey. Therefore it can be said that the data on which this report is based are more complete than for any other replacement alunite deposit. It is the purpose of this paper to record these new geologic data and to interpret them in an effort to explain the genesis of this particular deposit.

Acknowledgments.—The writers are indebted to Mr. Eugene Callaghan of the Geological Survey, U. S. Department of the Interior, for his continued aid both in the field and in the preparation of this manuscript. Thanks are due Mr. R. W. Martin, superintendent of the White Horse mine, without whose whole-hearted cooperation this paper would not have been possible. To B. S. Butler, Josiah Bridge, and G. F. Loughlin, thanks are also due for their critical examination of the manuscript. Many favors were extended by the people of Marysvale.

Location of Deposit.—The White Horse alunite deposit, one of many replacement deposits in the Henry mining district, is in sec. 10, T.27S., R.3W., about 4½ miles northeast of Marysvale, Utah. It is in the low hills to the south of the Antelope Range and just west of the mountainous front of the Sevier Plateau (Fig. 1). The altitude of the deposit is 6,400 feet or 600 feet above the shipping point at Marysvale, which is the terminus of a branch of the Denver and Rio Grande Western railroad. A well-graded two-lane access road extends from the mine to Marysvale.

GENERAL GEOLOGY.

General Statement.

The Marysvale area comprises pre-Tertiary sedimentary rocks, a thick series of earlier Tertiary extrusive rocks and associated intrusive quartz monzonite, a later group of Tertiary extrusive rocks, and the overlying late Pliocene or early Pleistocene Sevier River formation. All these groups are separated by marked unconformities. The alunite near Marysvale is limited to the earlier Tertiary extrusive rocks. The sequence of the Tertiary igneous rocks is described by Callaghan [6] as follows:

> "The extrusive igneous rocks . . . are divided into three principal groups on the basis of profound breaks in the sequence. The earlier Tertiary group, called the Bullion Canyon volcanics, is perhaps the most wide-spread. . . . It has the greatest economic importance of all the groups in that the mineral deposits (alunite) are confined to it. Largely made up of tuffs and volcanic breccias, it also contains a variety of latite-flows. Quartz monzonite and related intrusives are confined to it. An erosion interval separates the earlier Tertiary group from the later Tertiary group, for rhyolite of the later group rests directly on eroded quartz-monzonite. Rhyolite, latite, quartz latite, tuff and possibly a group of basaltic breccias . . . compose the later Tertiary group."

[6] Callaghan, Eugene: Volcanic sequence in the Marysvale region in southwest-central Utah. Nat. Research Council Trans. of 1939, Am. Geophys. Union, part III, p. 441, 1939.

The White Horse deposit is confined to a latite flow of the Bullion Canyon volcanics.

Structurally, the White Horse deposit is in an elongate valley block parallel and adjacent to the northward-trending Sevier fault which outlines the high

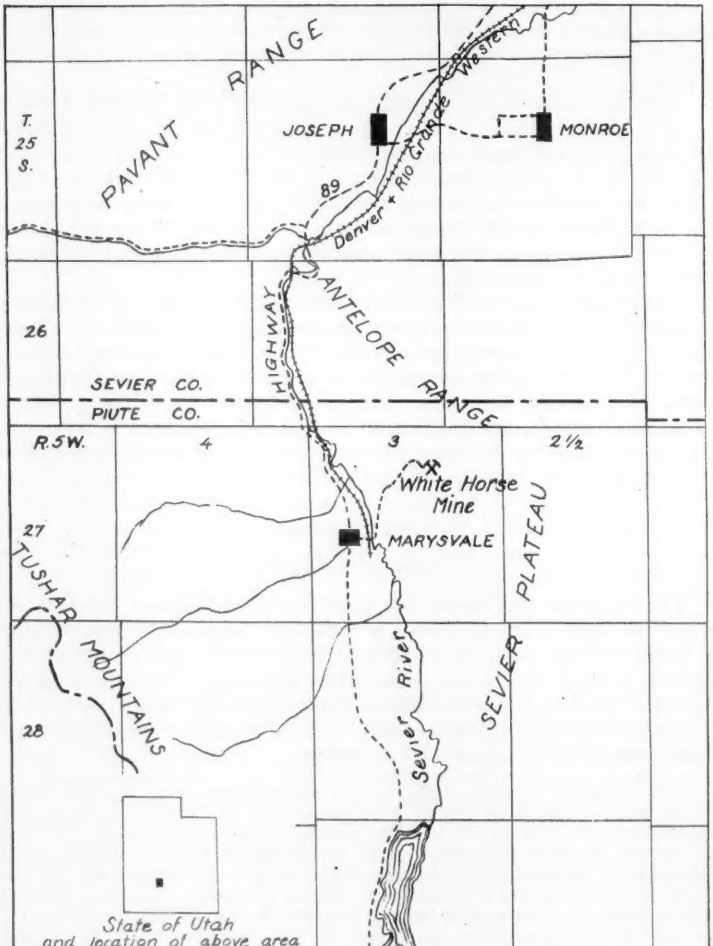

FIG. 1. Index map of the Marysvale region showing the location of the White Horse mine.

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Sevier Plateau to the east. To the north is the transverse anticlinal Antelope Range. The flows and volcanic breccias in the vicinity of the White Horse deposit dip gently to the southwest.

Latite.

At the White Horse deposit, except for a xenolith of quartzite, all the outcrops are of a single rock type, a calcic quartz latite, probably occurring as a single thick flow. Where unaffected by weathering or the alunite mineralization, the latite contains closely spaced phenocrysts of biotite and andesine in an aphanitic groundmass which is reddish brown to almost black. The phenocrysts are from 1 to 5 mm. long, the average being 3 mm. The andesine phenocrysts are in part euhedral and contain blebs of albite. These platy and prismatic phenocrysts are arranged so that their larger faces are roughly parallel. The groundmass of the rock is largely crystalline but most of the crystals are too small to be identified in thin section (Fig. 2, *a*). All the identifiable minerals in the rock are shown in Table I:

TABLE I.

	Norm	Mode
Quartz	12.30%	X
Orthoclase	30.02	
Albite	27.25	X
Anorthite	11.40	X
Corundum	4.18	
Hypersthene	10.00	
Magnetite		X
Hematite	1.28	X
Ilmenite	1.06	X
Apatite		X
Calcite		X
Biotite		X
Chlorite		X
	98.49	
	1.05 = water	
	99.54	

Within the groundmass of the rock there is a distinct concentration of the darker particles in parallel layers or streaks which wrap around the phenocrysts and are parallel to the platy structure produced by the orientation of the phenocrysts (Fig. 2, *b*). These combined features constitute a primary foliation, or flow structure, that gives the rock a layered appearance on weathered surfaces (Fig. 3, *a*).

Locally the rock may be quite vesicular or brecciated. The fragments and groundmass of the breccia are similar in texture and composition to the main mass. The fragments range from a fraction of an inch to a foot or more across, but the average is 4 inches. Locally the spaces between the breccia fragments have not been entirely filled and the rock is, therefore, porous.

When examined microscopically, the apparently fresh latite shows evidence of alteration that is not obviously related to the alunite mineralization. Most

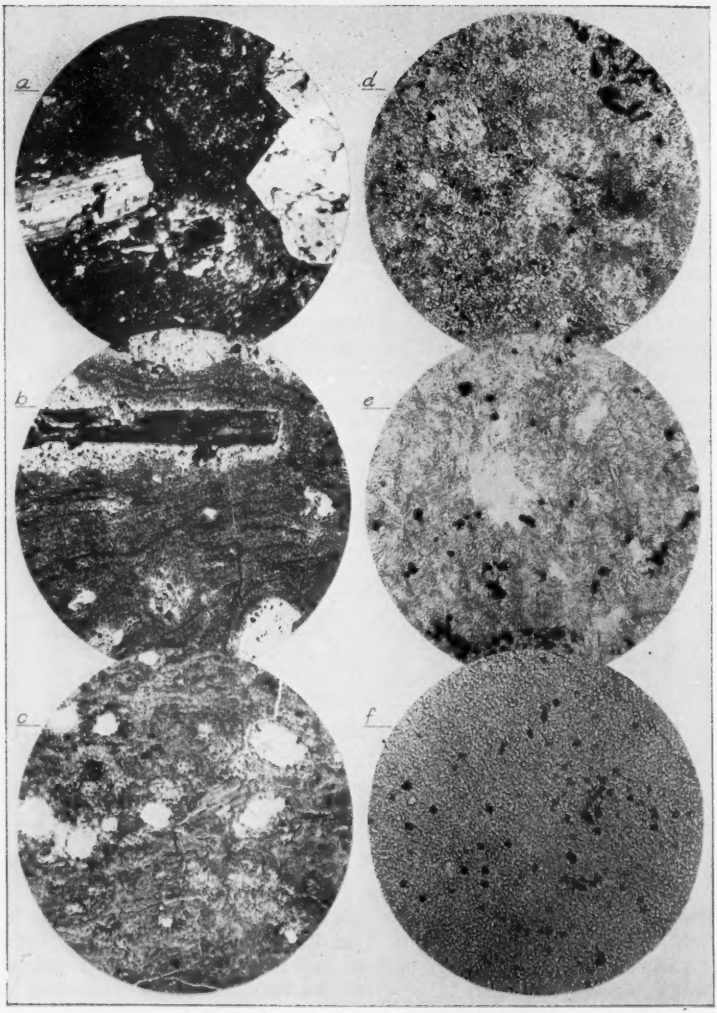

FIG. 2. Photomicrographs. *a*. Crossed nicols. Unreplaced latite shows andesine phenocrysts in stony groundmass. × 15. *b*. Flow structure in unreplaced latite produced by concentration of dark particles and parallel arrangement of phenocrysts. × 80. *c*. Kaolinized latite, irregular clear areas are albite. × 15. *d*. Alunitized latite, 51 per cent alunite. Small needle and plate-like crystals with high relief are alunite, groundmass is largely clay and quartz. Dark lath-like grains are leucoxene. × 80. *e*. Alunitized latite, 32 per cent alunite. Needle-like crystals are alunite. Dark areas are hematite. × 80. *f*. Material in small veinlets. Plate-like crystals of high relief are alunite. Dark areas are hematite. × 80.

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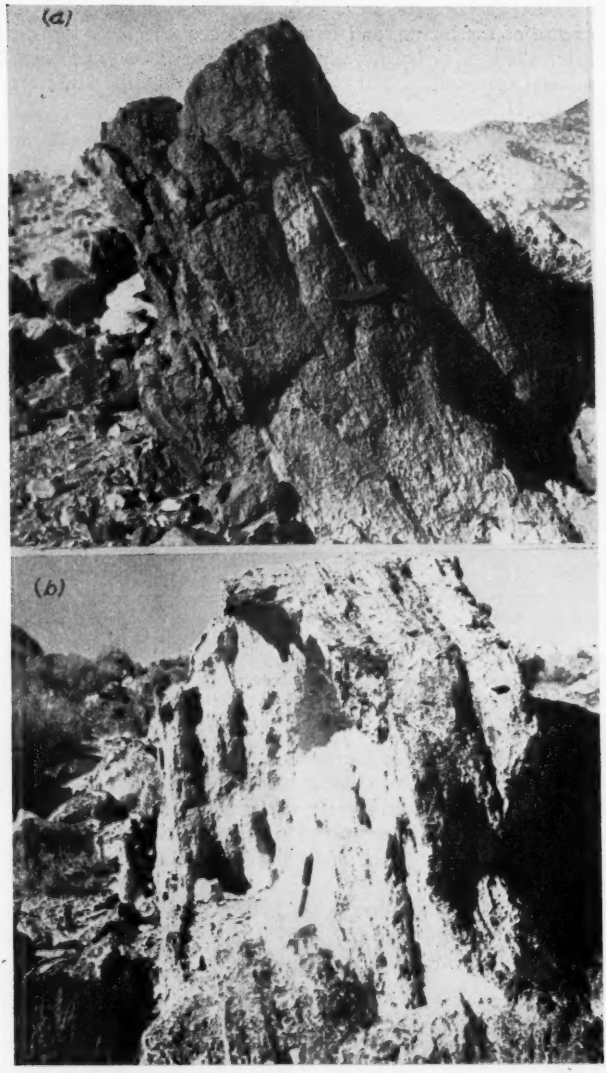

FIG. 3. (*a*) Small outcrop of latite showing flow structure. Trace of structure is parallel to hammer handle. (*b*) Highly altered latite with original flow structure still showing.

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of the andesine phenocrysts are highly sericitized, chlorite has developed at the expense of the biotite, and fringes of leucoxene have formed around grains of ilmenite. A carbonate mineral and quartz also have been formed.

The mineral composition and chemical character of the latite are shown in Tables I and II.

TABLE II.

CHEMICAL ANALYSES.

	1	2	3	4
SiO_2	60.47	64.72	47.88	13.40
Al_2O_3	19.29	17.59	20.33	31.55
Fe_2O_3	1.27	1.70	.97	.56
FeO	3.93			
MgO	1.54			
CaO	2.28			
Na_2O	3.24	3.43	.10	.79
K_2O	5.11	5.89	4.59	8.64
H_2O-	.44	.94	.10	.08
H_2O+	.61	4.67	6.82	10.54
TiO_2	.56	1.34	.62	.77
CO_2	.49			
P_2O_5	.02			
SO_3	None	.37	19.60	33.80
MnO	.38			
Total	99.63	100.65	101.01	100.13
Al_2O_3 (available)	3.02	3.84	18.77	31.23

Analyst: Cyrus Feldman.

Descriptions of specimens.

(1) Fresh latite—On "old road" at south end of White Horse deposit.
(2) Kaolinized latite between alunite lenses on east side of North ore body.
(3) Highly alunitized latite near south end of North ore body.
(4) Vein material—East side of Main quarry in North ore body (see Fig. 5).

The flow breccia and vesicular parts indicate that this latite occurs as a lava flow; there is no evidence that it may be intrusive. The alteration of the latite noted above and the alunite mineralization are considered by E. Callaghan [7] as features characteristic of the Bullion Canyon volcanics; and he suggests that the calcic latite flows belong to the upper part of these volcanics.[8]

The thickness of this latite flow is not known. At no place in the area is the bottom of the flow exposed and it was not reached during exploration, which proceeded to a depth of 300 feet.

Alteration.

Distribution and General Description.—In common with most of the replacement deposits of the Marysvale region, the altered rock at the White Horse deposit consists largely of alunite, kaolinite, and quartz in varying

[7] Callaghan, E.: Nat. Research Council Bull. Am. Geophys. Trans. of 1939, part III, p. 446.

[8] Callaghan, E.: *op. cit.*, p. 443.

proportions with minor amounts of iron oxide and leucoxene. The rock has been both alunitized and kaolinized, the effects of these processes generally being superimposed. It is, therefore, necessary to speak of kaolinized or alunitized latite, depending upon which process has dominated.

The alteration is largely confined to boat-shaped bodies that are arranged with their long dimensions about parallel and trending a few degrees west of

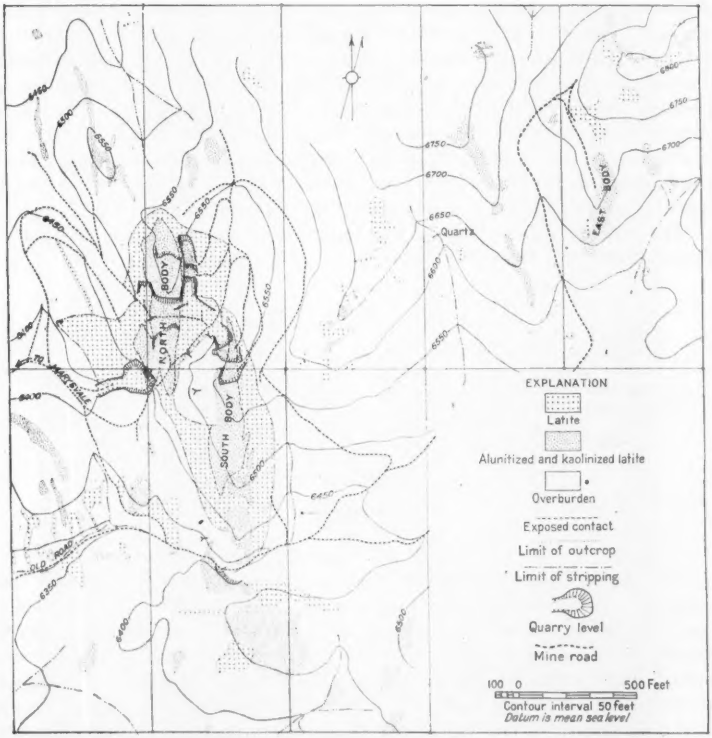

FIG. 4. Index and outcrop map of White Horse alunite deposit. Correction: "Quartz" in upper right corner should read "quartzite."

north. The number of these bodies within a unit area is variable; they may be so closely spaced that they touch (Fig. 4). In these bodies of altered rock there is a constant field relation between the alunitized and kaolinized parts. A central area of alunitized rock that is roughly boat shaped is always surrounded by an envelope of kaolinized latite which grades outward into unaltered rock. The alunitized parts of these bodies have been the most resistant to weathering and therefore stand out in large outcrops.

Mineralogic Changes.—In the outer parts of the kaolinized envelopes that surrounded the alunite bodies the andesine phenocrysts of the latite are completely changed to a mixture of clay and sericite; but the groundmass and other mineral grains are unaffected. The kaolinized latite in these outer parts of the envelope retains its original textures and structures. It also retains its dark color or is slightly bleached to a purplish-gray, and when exposed to surface weathering has a tendency to crumble. The inner parts of these envelopes of kaolinized latite are highly bleached, the biotite flakes are light colored or are completely absent, and the andesine phenocrysts are altered to light-green clay masses that after exposure dry out and turn white. Clarence S. Ross of the United States Geological Survey has identified the greenish clay of these altered phenocrysts as largely kaolinite. The altered phenocrysts commonly contain a very few small, delicate, needle-like crystals of alunite. In the most highly kaolinized rock the identifiable minerals of the groundmass are kaolin, microscopic grains of quartz, a fine dust of mixed hematite and leucoxene, and scattered grains of fresh albite (Fig. 2, *c*).

The mineral composition of the kaolinized latite as calculated from the ultimate analysis (Table II, column 2) is shown in Table III.

TABLE III.

Quartz	17.34	
Orthoclase	34.46	
Albite	27.77	
Kaolinite	14.02	
Limonite	1.76	
TiO_2	1.36	(leucoxene)
Alunite	.72	
	97.43	
	3.53	= (residual H_2O)
	100.96	

The change from dominantly kaolinized to dominantly alunitized rock is abrupt, commonly occurring within a few inches; but within the zone of change the rock is noticeably more silicious, and alunite and kaolinite may be present in nearly equal amounts. Typically there is within this zone a marked increase in the amount of hematite. From the zone of change to the center of an altered body the percentage of alunite increases. Assays show a maximum of between 55 and 60 per cent alunite in the central parts.

The highly alunitized latite consists mainly of small needle- or plate-like crystals of alunite, seldom more than a few microns long, disseminated in a groundmass of extremely fine-grained quartz and clay. Commonly there is also present a rather uniformly distributed dust of hematite and small lath-like grains of leucoxene (Fig. 2, *d*, *e*). The highly alunitized rock is mostly chalky white, and noticeably heavier than the less altered rock; the porphyritic texture of the original latite is only faintly evident. Many of the relict phenocrysts, even in this highly alunitized rock, are predominantly clay. The flow structure in the highly alunitized latite is clearly evident on weathered surfaces but otherwise may not be apparent (Fig. 3, *b*). Where alteration

has been less severe the alunitized latite may range from pink to lavendar depending on the amount of iron remaining, and, as would be expected, the original textures and structures of the latite are quite apparent. Locally this less altered rock is porous, as though the vesicular nature of the original latite had somehow remained.

FIG. 5. Veinlet of alunite (white) cutting alunitized and kaolinized latite (light gray). Veinlet strikes parallel to the plane of picture.

There are, within the alunitized masses, small veinlets or pods of an extremely soft white powdery material that is predominantly alunite and quartz (Figs. 2 (*f*) and 5). The small amount of Na_2O in this material (4–Table II) is probably present as natroalunite in an isomorphous mixture with the alunite. A part of the Na_2O in the replacement ore may also have the same occurrence. Natroalunite was not identified in any of the ore from the White Horse, but it is conspicuous at the Yellow Jacket where it occurs

mainly in veinlets that cut the replacement ore. Natroalunite has also been reported by Callaghan [9] in other deposits of the Marysvale region.

Chemical Changes During Alteration.—The percentages of the most abundant substances in the fresh, kaolinized and alunitized latite as shown in

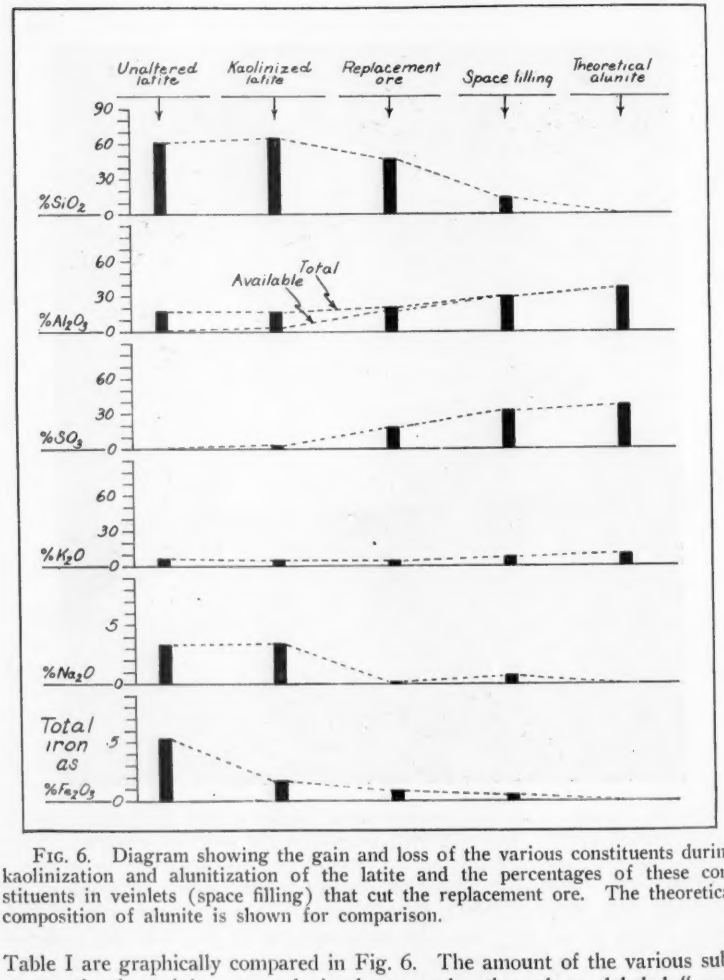

FIG. 6. Diagram showing the gain and loss of the various constituents during kaolinization and alunitization of the latite and the percentages of these constituents in veinlets (space filling) that cut the replacement ore. The theoretical composition of alunite is shown for comparison.

Table I are graphically compared in Fig. 6. The amount of the various substances in the veinlets or pods is shown under the column labeled "space

[9] Callaghan, Eugene: Preliminary report on the alunite deposits of the Marysvale region, Utah. U. S. Geol. Survey Bull. 886–D, pp. 127–129, 1937.

filling." The amount of these substances in pure alunite is also given for comparison. The average specific gravity of both the latite and the alteration products is 2.62; therefore, assuming no change in volume during alunitization, the changes in percentages of the various oxides as shown in Fig. 6 can be considered as the relative weight changes per unit volume of rock replaced.

During kaolinization the SiO_2 content of the latite is not appreciably changed. There is a small loss in Al_2O_3, and a part of the total Al_2O_3 is released from the silicates and combined in a form that is subject to leaching with dilute sulphuric acid. A small amount of SO_3 is added, as indicated by the tiny crystals of alunite previously mentioned. Apparently there is a slight loss of K_2O and Na_2O, and all of the CaO is removed. A large part of the iron is also removed, but some of it remains as hematite or in residual silicate minerals.

During alunitization the latite looses from 10 to 15 per cent silica, and gains 15 to 23 per cent SO_3. The K_2O content remains constant, but most of the sodium and iron that it originally contained are lost. It should be noted that all of the iron that remains in the alunitized rock occurs as hemaite; no pyrite was seen.

Conclusions.—The alteration to alunite was produced by a sulphate-bearing solution that reacted with the original constituents of the latite, taking into solution, in addition to potash and alumina, all the sodium together with a part of the iron and silica. A large part of the released potash and alumina was immediately deposited as alunite but some remained in solution. It seems likely that the veinlets or pods of chalky alunite represent the filling of open spaces by this enriched solution. Most of the dissolved silica and iron were carried beyond the present areas of alunitization before they were deposited. The sodium that went into solution was also removed unless the potash originally present in the latite was not sufficient to exhaust the solution by combination with the SO_3. If, on the other hand, the available SO_3 was in excess of that necessary to combine with the potash present in the rock, natroalunite was formed.

The intimate mixing of the kaolin and alunite and the distribution of the kaolin as an envelope about the alunitized masses strongly suggest that the two are genetically related. The small euhedral crystals of alunite in the kaolinized phenocrysts of the latite and growing inward from the outer edges of these phenocrysts suggest that the kaolin developed first. The writers are of the opinion that the advancing sulphate-bearing solution partly kaolinized the latite, thus preparing it for later alunitization.

The evidence at the White Horse deposit does not definitely establish the origin of the mineralizing solution. Most of the observed chemical and mineralogic characteristics could have been produced by a sulphate-bearing solution of either deep-seated or surface origin. The lack of pyrite in all the rocks of the deposit, without evidence of it ever having existed in quantity, makes it doubtful that the mineralizing solution developed from the oxidation of that mineral. Nonselective replacement of the minerals of the latite and replacement in large part independent of evident fractures suggest that the solution was hydrothermal. The regional distribution of the replacement

alunite in an aureole about an exposed stock of quartz-monzonite, as pointed out by Callaghan,[10] strongly suggests that it overlies the source of at least a part of the mineralizing solution. Therefore, the writers are of the opinion that the alunite at the White Horse deposit was formed by a sulphate-bearing solution that was largely produced at depth possibly from the oxidation of hydrogen sulphide of magmatic origin.

STRUCTURE.

The general strike and dip of the latite flow cannot be established at the deposit for, as mentioned earlier, the base of the latite is not exposed and the strikes and dips of the flow structure vary from place to place. Outside of the area mapped, however, several large outcrops of the latite indicate that the flow as a whole dips gently southwest. At the White Horse there are, superimposed on this simple structure, prominent primary and secondary structures. These include flow structure, flow breccias, joints, and minor faults.

Primary Structure.—The flow structure in the latite is conspicuously exposed in all the prominent outcrops of the deposit, both altered and unaltered (Fig. 3). In the southwest part of the area the flow layers are isoclinally folded and this folding is reflected in the outcrop pattern. The folds in this part of the area strike north, are slightly overturned to the west, and plunge a few degrees south. Near the far south quarry on the "old road," the flow planes dip from 15° to 20° E. or W., indicating that the flow folding there is slight. The mapped synclinal fold at the south end of the South ore body, as shown in Fig. 10, strikes a few degrees west of north and plunges south about 40°. Near the south end of the South ore body are several small synclines and anticlines. One of the synclines strikes a little east of north and has a 3° plunge to the north. South and east of this fold are smaller folds the limbs of which dip as much as 78° either E. or W. At least two synclinal troughs are indicated in the north end of the South ore body. The axial planes of these synclines correspond in strike and dip to the trend of the alunite body.

There are synclinal and anticlinal folds in the flow structure of the North ore body, which strikes a little west of north; the limbs of these folds dip 70°–80° E. and W. and have an indicated plunge to the south. The large folds in the North ore body have been traced for more than 200 feet along their strike (Fig. 8). In the northwest corner of the area mapped an eroded anticlinal fold crops out, which strikes and plunges approximately north. One limb dips 70°–80° E. and the other dips 45°–60° W. Parts of other flow folds are exposed north and east of the North ore body and east and north of the South body (Fig. 4).

In the East ore body there is one complete syncline which trends about N. 10° W. and plunges southward (Fig. 12). A northeast-striking limb of a rather gentle fold crops out north of the East ore body.

The attitude of the flow-structure, where exposed, permits the following generalizations:

[10] Callaghan, E., Oral communication.

1. Folds of the flow structure are abundant. They are all roughly parallel, and their axial planes strike a few degrees west of north and dip steeply east.
2. Most of the folds plunge gently south.
3. The severity of folding decreases from north to south in the area mapped.
4. The folds vary greatly in size. Many of the small irregularities inherent in a primary flow structure are present.

The vesicular latite and flow breccia are exposed at random throughout the area. These features occur principally in the fold troughs north of the "old road" and are present in either the alunite bodies or the unaltered rock. South of the "old road," flow breccia occurs in a thin surface layer that is almost horizontal.

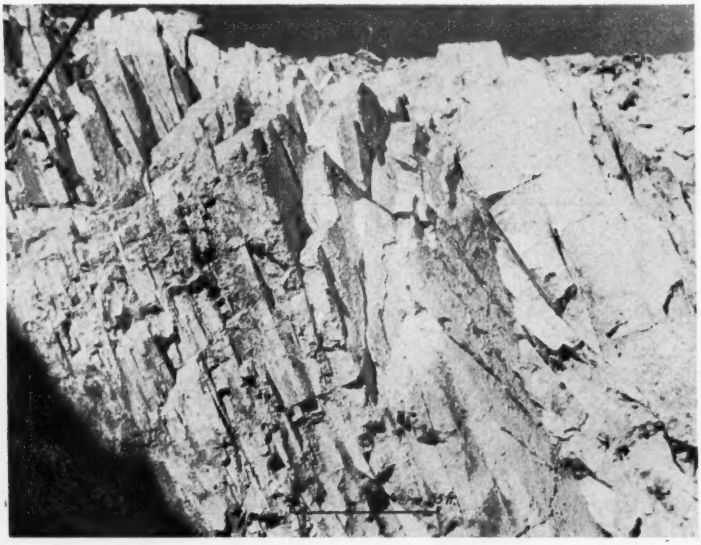

FIG. 7. Jointing in kaolinized latite, east side of North ore body.

Secondary Structure.—Four sets of joints cut the alunite-bearing rock. They strike N. 22° E., N. 68° E., N. 20° W., and east; their dips are all nearly vertical. Some movement has occurred on the east-striking joints as indicated by slickensides with striae parallel to the strike of the joint planes. Minor slickensiding also occurs on the N. 20° W. set in the South ore body. The striae on this set are about perpendicular to the strike of the joints. None of the above joint sets are present outside of the alunitized areas. Prominent closely spaced joints occur in abundance parallel to the outer contacts of the alunite bodies (Fig. 7). The abundance of these joints varies directly with

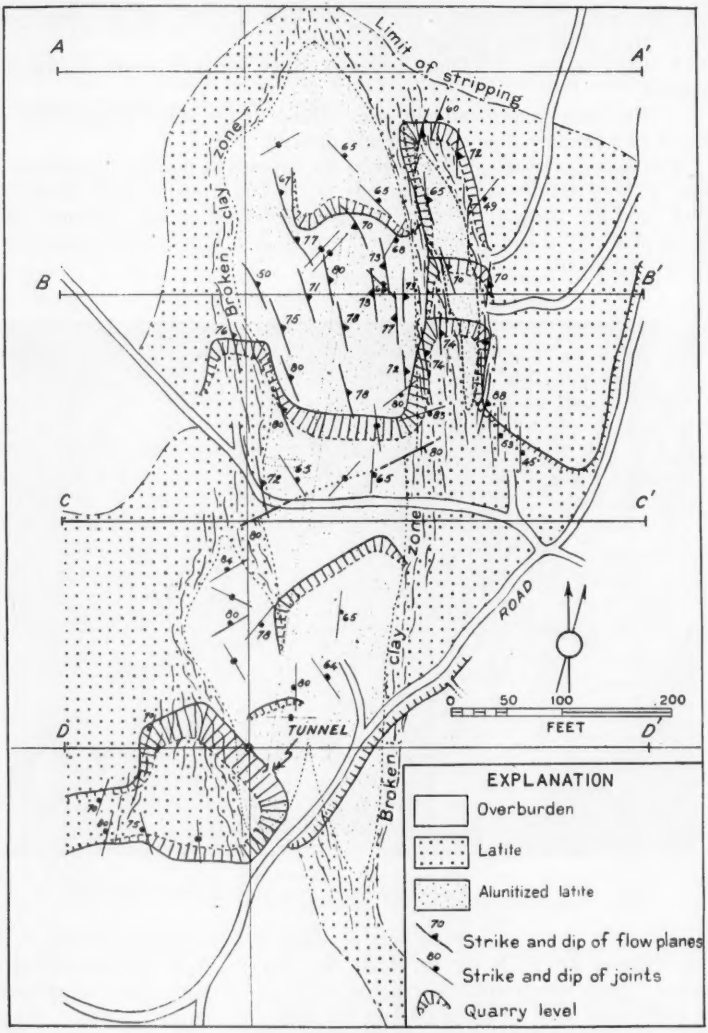

FIG. 8. Geologic map of the North ore body.

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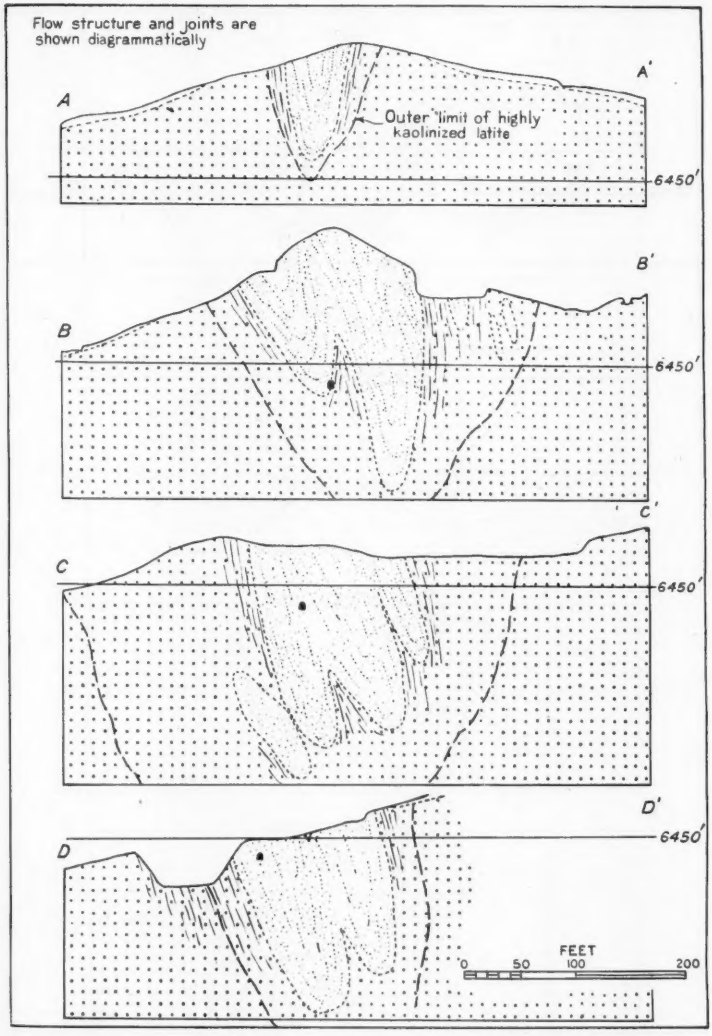

FIG. 9. Geologic sections across the North ore body (for location of sections and explanation see Fig. 8).

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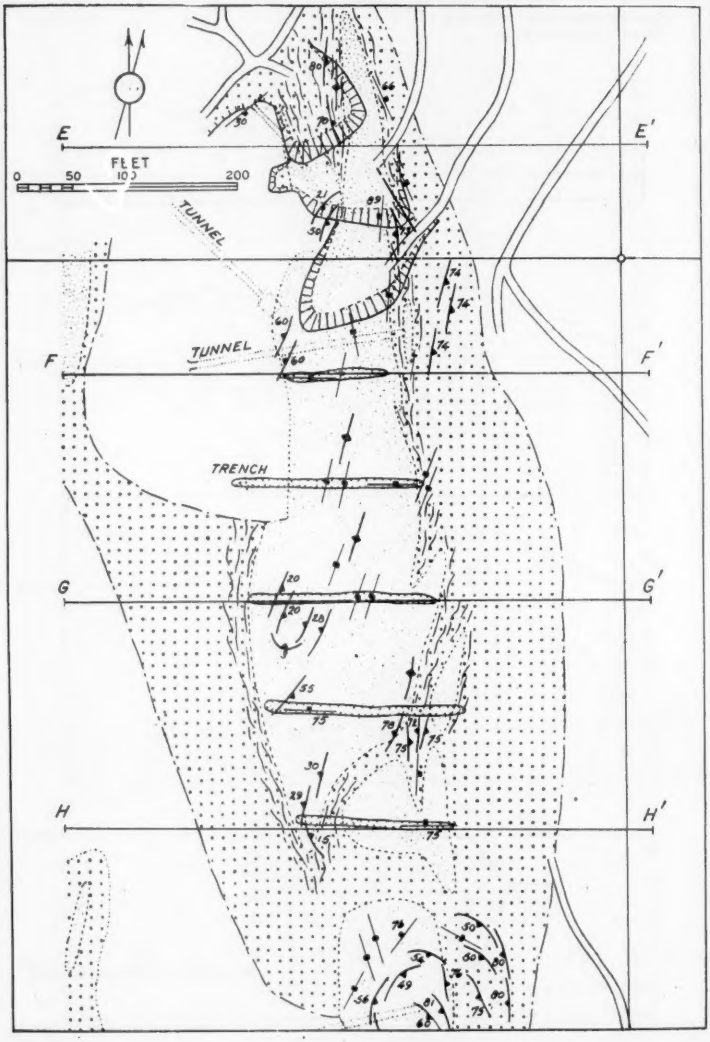

FIG. 10. Geologic map of the South ore body (for explanation see Fig. 8).

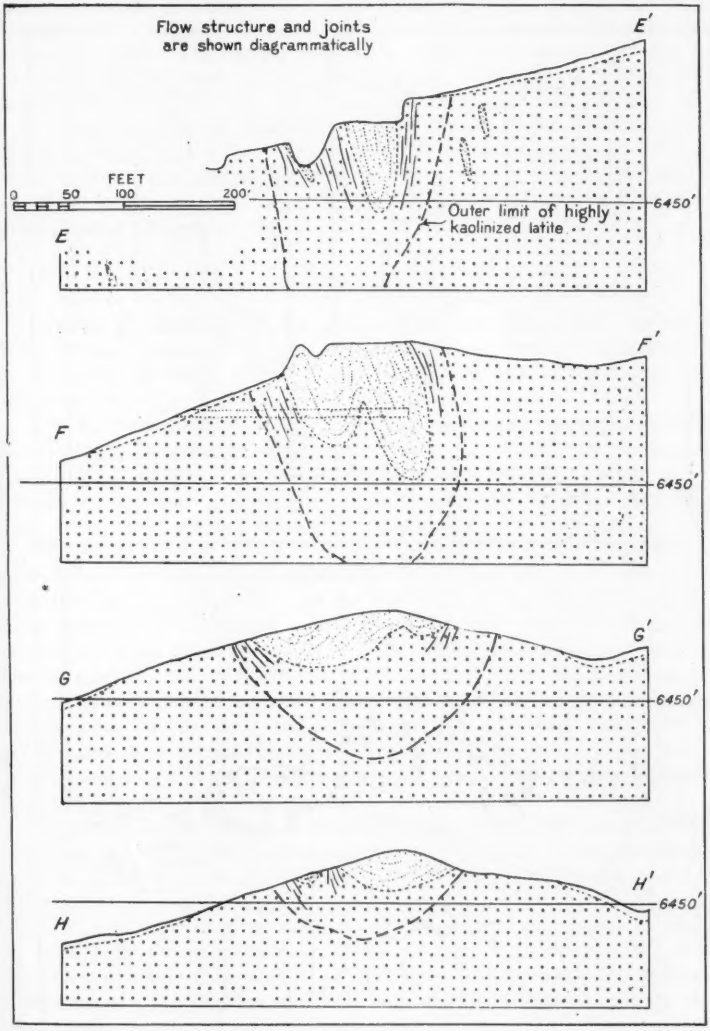

FIG. 11. Geologic sections across the South ore body (for explanation see Fig. 8).

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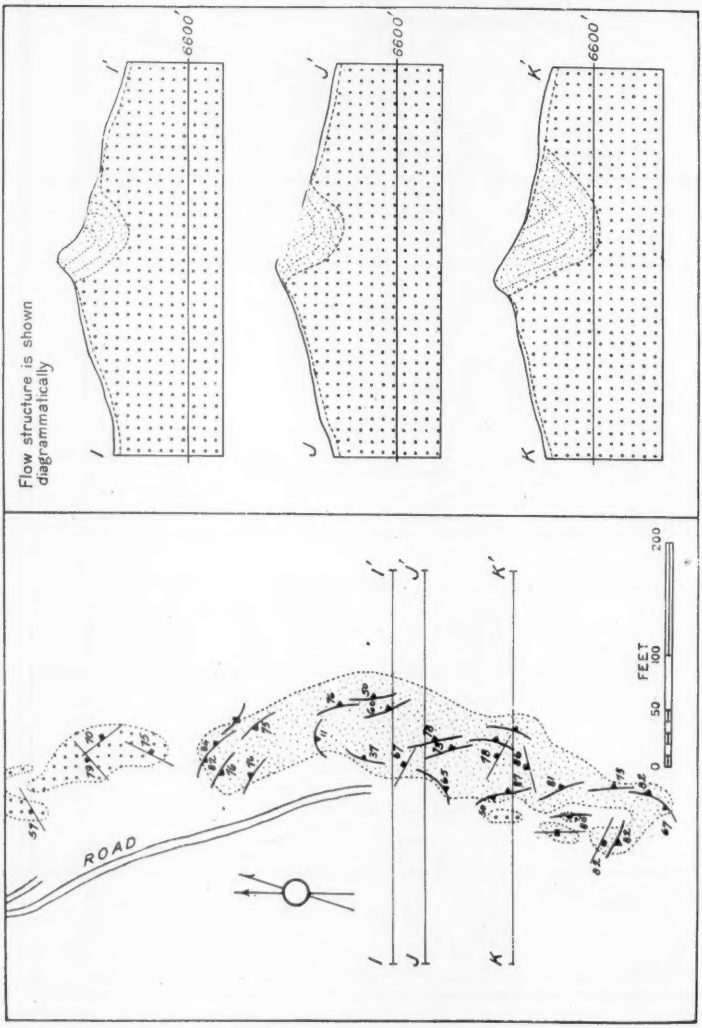

FIG. 12. Geologic map and sections of the East ore body.

their distance from the outer contacts of the ore. At the contacts they are only a few inches apart, and the distance between them is greater the farther they are from the contacts. This jointing continues only a short distance in the altered latite. The same relationships exist across the contact and into the alunite-bearing rock. Locally these joints may coincide with the flow planes.

A small post-mineral fault with a strike-slip of 15 feet cuts the central part of the North ore body. It strikes N. 67° E. and dips 80° S. As mentioned above, some slickensides occur on some of the joint planes, but the movement on these planes was slight; no measurable displacement of the alunite bodies occurred.

ALUNITE BODIES.

General Description.—In the White Horse area the alunite bodies are easily distinguished from the unaltered latite, for they form prominent brownish weathered outcrops. The three main alunite bodies are the North, South and East (Fig. 4).

The main alunite mass of the North body consists of two coalescing lenses which form a lenticular outcrop 740 feet long with a maximum width of 160 feet (Figs. 8 and 9). The lenses that make up this mass trend N. 10° W., dip steeply east, and continue to a depth of more than 100 feet. The central parts of these lenses are noticeably porous; tests by Kalunite, Inc., have shown a porosity of at least 15 per cent. The lenses of the North body are surrounded by a zone of kaolinized latite that ranges from a few feet to more than 100 feet wide (Fig. 9). At the south end and on the west side of the main North body is a small lens of alunitized rock which is 260 feet long and 90 feet wide at its widest part. This lens coalesces with the main body near its southern end. On the east side of the main North body and separated from it by a 20-foot zone of kaolinized latite is another small lens of alunite-bearing rock 260 feet long and 35 feet wide at its widest part. This lens pinches out about 30 feet below its lowest surface exposure. In section, each of the ore masses in the North body is somewhat boat-shaped, dips steeply east, and plunge south (Fig. 9).

As shown in Fig. 9 the flow structure in the main north lens is folded into synclines and anticlines overturned to the west. The thoroughly alunitized rock in this area is largely restricted to the fold troughs and reaches its greatest depth along the axes of the fold troughs. The conformance between the plunge of the North ore body and the observed south plunge of the folds is evident in the cross-sections shown in Fig. 9. Information for these sections was obtained from diamond drill holes, which crosscut the body every 100 feet for its full length, and from a north-south drift that follows the length of the body.

In general the South alunite body is similar to the North in that it is made up of several coalescing lenses that strike approximately north and dip steeply east (Fig. 10). This body is also surrounded by an envelope of kaolinized latite. The depth of the South body below the present erosion surface

FIG. 12. Geologic map and sections of the East ore body.

is variable, as shown in Fig. 11. It reaches a maximum depth of 100 feet near its north end.

The relation of the South body to the flow structure of the latite is even more apparent than in the North body. There is a syncline at the north end of the South body and further south, near section FF', Fig. 11, there are two more complete folds; here again the greatest depth of alunitization is in the synclines. At the south end of the South body, as indicated in section GG', Fig. 11, the alunite continues only a short distance below the surface. The flow layers in this area are gently folded into a syncline that plunges three degrees north and strikes parallel to the trend of the alunite body. The attitude of the flow layers in the far south lens of the South body south of section HH', Fig. 10, indicates that this lens also occupies a north trending fold trough that plunges about 40° S.

The East body is more than 400 feet long and has a maximum width of 100 feet. This body is roughly lenticular in plan, strikes approximately north, dips steeply east, and plunges to the south (Fig. 12). It consists of at least one large lens and another much smaller one. Like the North and South bodies, the East body is also surrounded by a zone of kaolinized latite. The flow layers in the East body, as already noted, are folded, and here again diamond drilling has indicated that the greatest depth of mineralization was in the fold troughs.

Distribution of Grades.—Grade variations across the North ore body, as shown by surface channel samples along the lines of sections AA', BB', CC', and DD', Fig. 8, are graphically shown in Fig. 13. The parts of the graphs showing the highest alumina and sulphate contents correspond closely to the axial planes of the indicated fold troughs. The high points on the graphs usually occur midway between the outer limits of the known alunite lens and above the areas in which the depth of alunite is greatest.

The zones of kaolinization are indicated in the graphs by a sudden drop in sulphate and a gradual decrease in the "available" alumina. It should be pointed out that the lows in these graphs, within the limits of the alunitized area, are not marked at the surface by visible changes in the rock. In a given lens there is no systematic variation in the grade of the alunite along its strike.

GENESIS.

The relations of the alunite bodies to the observable structures at the deposit, and the chemical gain and loss of material during alteration, as already discussed, seem to justify certain conclusions concerning the genesis of this alunite deposit.

The sequence of events at the White Horse deposit seems to have been as follows (Fig. 14):

1. A latite lava flowed over the area.

2. Continued flow of this lava produced an orientation of the intratelluric crystals and the development of a platy flow structure.

3. Expanding vapors produced a vesicular layer of varying thickness at the upper surface of the flow. Continued flow of material under a thin crust of chilled lava locally produced a flow breccia.

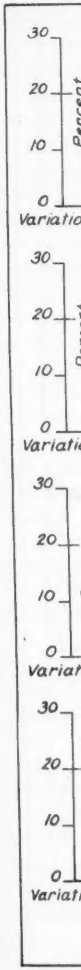

FIG. 1
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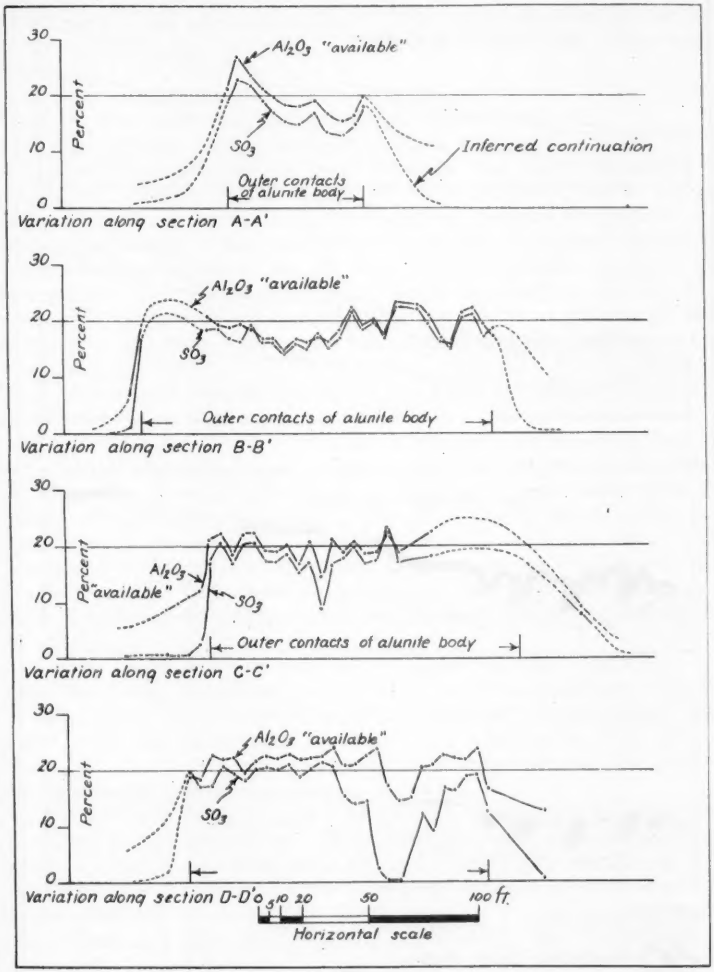

FIG. 13. Grade variations at the surface across the North ore body along lines of sections AA', BB', CC', and DD', Fig. 8. Based on channel samples taken every 5 feet for the width of the body. Data supplied by Kalunite, Inc.

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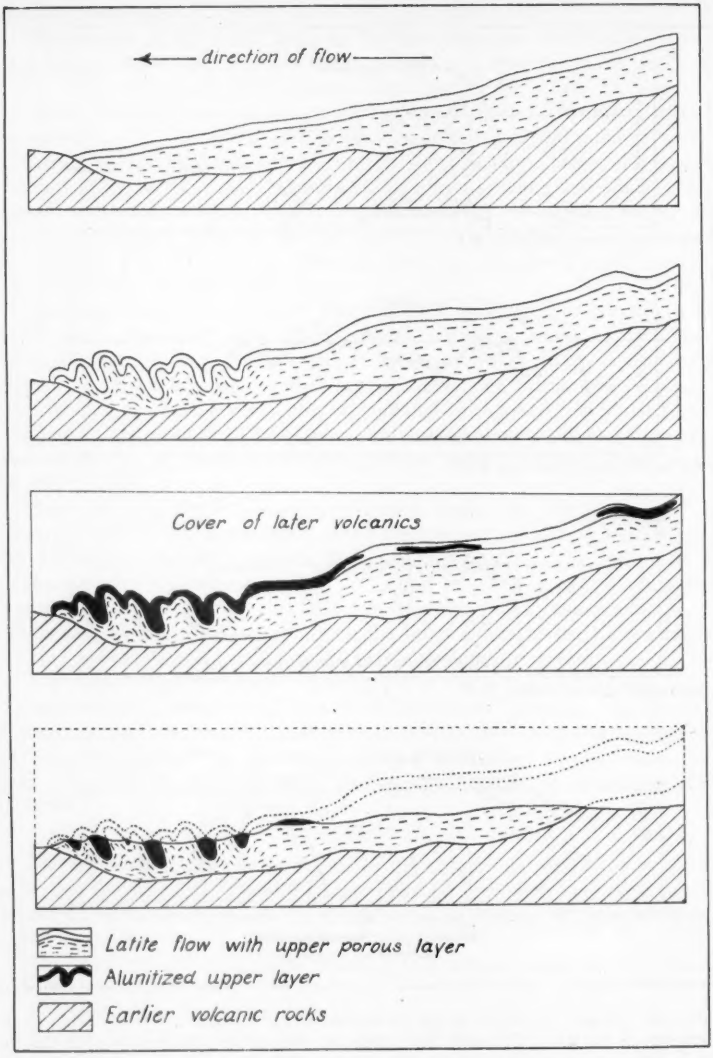

FIG. 14. Synoptic diagram showing the development of the White Horse deposit.

4. Frictional drag at the bottom of the flow plus topographic irregularities that locally impeded the flow of lava caused isoclinal flow folding which infolded parts of the upper porous layer. (As previously noted all the folds are overturned to the west which suggests that the lava flowed from east to west.)

5. After solidification this lava was very probably covered by later volcanic rocks, but these have since been completely eroded.

6. The infolded upper porous layer made a series of troughs for the circulation of any solutions that found their way into them. Apparently the mineralizing solution entered these channels of circulation outside the area of the White Horse deposit, for at the deposit the alteration was generally confined to the troughs. This relationship suggests that the mineralizing solution was confined to and moved laterally along the fold troughs. Since the solution was thus directed through a small volume of rock it was able to alter it completely. Where folding was absent or less severe, as for example south of the "old road," the solution was less confined and the alteration was not so complete.

7. Post-mineral erosion has left, in the main, the infolded parts of the alunitized and kaolinized upper layer.

Support for the above conclusions is found in the following facts: all the workable alunite bodies are located in synclines and are comformable in dip and strike with the axial planes of these folds; the alunite bodies also plunge with the axes of the folds; none of the alunite bodies extend down to a depth in excess of the known amplitude of the larger folds. Stated briefly, the essential structural features necessary for the development of the ore bodies at the White Horse deposit seem to have been development in the latite of an upper porous layer and the infolding of that layer during flow folding.

Locally minor structural adjustments, concurrent with replacement, brecciated the already replaced latite and the open spaces produced were filled with alunite. These filled fractures cannot be interpreted as representing feeder channels for the circulation of the ore-making solutions, for their walls are sharp and there is no relation between their occurrence and the degree of alteration in the surrounding latite.

The most abundant and evident joints at the deposits are those that occur in a zone surrounding the ore. Their character and distribution, as already described, indicate that these joints developed largely after the mineralization. It follows, then, that they did not control the localization of the ore, and it is the opinion of the authors that, instead, they are a result of the mineralization. Detailed data on this point are not available, but it is possible that very slight changes in mass during mineralization of the latite might easily have been sufficient to produce them.

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SOUTH HADLEY, MASS.
March 14, 1946.

ARTIFICIAL RECHARGE OF GLACIAL SAND AND GRAVEL WITH FILTERED RIVER WATER AT LOUISVILLE, KENTUCKY.

W. F. GUYTON.

ABSTRACT.

Records obtained by the Geological Survey, United States Department of the Interior, and the Geological Division, Kentucky Department of Mines and Minerals, indicate that industries at Louisville pumped about 62 million gallons of water per day from wells in 1943. This was over 20 million gallons a day more than the natural recharge to the glacial outwash sand and gravel from which the wells draw the water. The ground water is especially in demand because of its uniformly low temperature throughout the year. In order to stop the resulting serious decline of water levels and decrease in yields of wells, the pumpage is now gradually being reduced. Also, the recharge has been increased about 2 million gallons a day by introducing water into the aquifer through wells.

During the spring of 1944 the Seagram and National distilleries helped solve a local shortage of ground water by recharging the underground reservoir with 1.7 million gallons a day of cold water from the municipal river-water supply. While this water was being added to the aquifer through several supply wells the plants were operated with additional city water, and the rest of the supply wells were kept idle. In this way, the large cone of depression in the water table that had been created by heavy pumping from the wells was practically filled with cold water from a combination of natural and artificial recharge. As a result, during the summer when the city water became too warm to be used in the plants, an increased and ample supply of cold water was available from the wells. It has been suggested that other industries at Louisville might adopt similar procedures for insuring adequate supplies of cold water during the summers.

GENERAL DESCRIPTION OF PROBLEM.

An investigation of the ground-water resources of the Louisville area, Kentucky, has been in progress since September 1943 by the Geological Survey, U. S. Department of the Interior, in cooperation with the Division of Geology, Kentucky Department of Mines and Minerals. Several reports and papers have been released on the work and are listed at the end of this paper as part of a general bibliography on ground water in the Louisville area.

The Louisville area, as the term is used in this paper, is comprised of the City of Louisville, in Jefferson County, Kentucky, and adjoining localities in Kentucky within a radius of several miles. Although the municipal water supply for Louisville is obtained from the Ohio River, industries in the area have pumped large quantities of water for many years from wells that draw from the glacial outwash deposits that underlie the river valley. This ground water is of fairly good chemical quality and is especially in demand for cooling

purposes because of its uniformly low temperature throughout the year. Also, in the past, ground water has been cheaper and easier to obtain than city water in many parts of the river valley.

As a result of the war the ground-water pumpage was increased about 65 per cent, from 37 to 62 million gallons a day. This has caused a continuous decline in the water table over the entire area, and several large cones of depression have been created in it around localities of extra heavy pumping. The water levels in a number of wells have dropped below pump intakes, necessitating the lowering of the intakes and in some cases deepening of the wells. Because the water-bearing sands and gravels are relatively thin the yields of the wells have decreased as the water levels have declined. In some localities critical shortages of ground water have developed.

The investigation has shown that the natural recharge to the ground-water reservoir is insufficient to supply the increased demand, and it has been recommended that the pumpage from the present well fields be reduced to less than 40 million gallons a day. The industries are now taking the necessary steps to make this reduction, but it is a time-consuming and costly procedure. By the time sufficient conservation measures are completed or new sources of water are developed by the various plants, several years will have past and several million dollars will have been spent. In the meantime, the water levels in wells will continue to decline, and many more plants will experience water shortages. Every effort is therefore being made to speed up the conservation measures and the development of new sources so that these occurrences will be kept to a minimum.

This paper is a brief review of the more important facts brought out by the investigation, with emphasis on one of the possible solutions to the shortage, namely, artificial recharge of the ground-water reservoir with cold city water during the winter.

Geology.—Most of the Louisville area is in the Ohio River valley on unconsolidated glacial outwash and other river deposits of Pleistocene and Recent age. The valley was originally cut in limestone, shale, and tightly-cemented sandstone of Silurian, Devonian, and Mississipian age, and is bounded on both sides by hills of these rocks. Nearly all of the large ground-water supplies developed in the area are obtained from the glacial outwash deposits which partially fill the old river valley; usually only small supplies are obtained from the underlying and adjoining older consolidated formations.

In the Louisville area the valley runs northeast and southwest, and at Louisville it is over six miles wide. Northeastward its narrows rapidly until about eight miles from Louisville it is only 1¼ miles wide. To the southwest of Louisville it becomes narrow more gradually, being about 1½ miles wide 19 miles southwest of Louisville. The river flows through the central part of the valley in the northeastern part of the area and along or near the northwestern margin southwest of Louisville. Louisville is on the southeastern side of the river, and Jeffersonville and New Albany, Indiana, are on the northwestern side. The elevation of the land surface of the valley ranges from about 425 to about 475 feet above mean sea level, averaging about 460 in Louisville. Above the dam at Louisville the normal pool stage of the

river is 420 feet above mean sea level and below the dam the normal pool stage is 383 feet.

During the Pleistocene epoch, the size and shape of the valley were greatly affected by the meltwater from the Illinoian and Wisconsin ice sheets. This meltwater eroded the consolidated rocks to a maximum depth of nearly 130 feet below the present land surface, and then partially filled the resulting deep valley with outwash sand and gravel. In more recent times this sand and gravel has been covered with about 5 to 30 feet of river clay, silt, and fine sand, which comprise the present surface materials.

Elevations of the top of the bedrock beneath the glacial outwash deposits are shown in Fig. 1 by means of contour lines based upon the reported depths

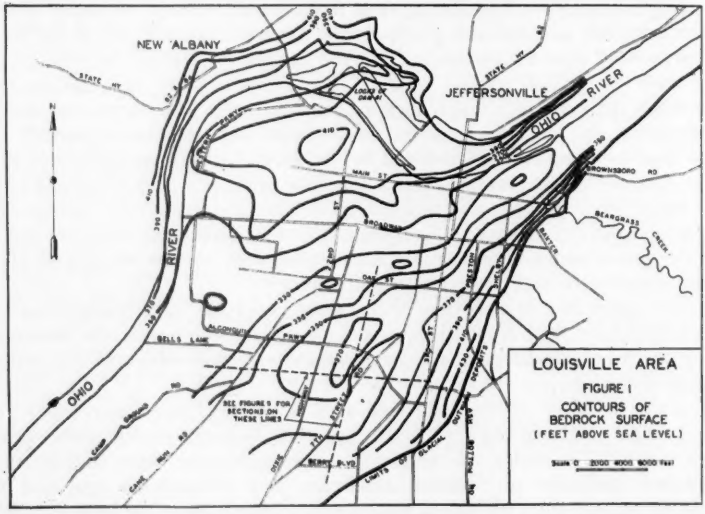

FIG. 1. Map of the Louisville area showing contours of bedrock surface.

to rock in over 340 wells, test borings, and river soundings. A large well-defined channel in the bedrock runs southwest under the area from the vicinity of the mouth of Beargrass Creek. In the middle of Louisville this main channel is about 1 to 1½ miles wide, and becomes wider to the southwest. Two tributary channels are also indicated by the contours.

The outwash sand and gravel overlying the bedrock in general varies inversely in thickness with the elevation of the bedrock surface, the thickness ranging from a featheredge in the marginal areas of the valley to over 125 feet in the main channel in the bedrock. Logs show that this sand and gravel is made up of interbedded lenses of gravel, coarse sand, medium sand and fine sand, with gravel or coarse sand predominating. The lenses range in thickness from a few inches to as much as 20 feet. Occasional lenses of well-

sorted medium or fine sand are found. Lenses of well-sorted gravel are extremely rare. The lenses contain varying small quantities of finer material but are not clay- or silt-bound. Clay and silt lenses are seldom present, and when present are thin.

Pumpage.—Table 1 is a compilation of records of the pumpage from all large wells in the area for the years 1937 through 1944. The areal distribution of the pumpage during 1943, which is the year that the pumpage was greatest, is shown by Fig. 2. Most of the heavy pumpage shown in the southwestern

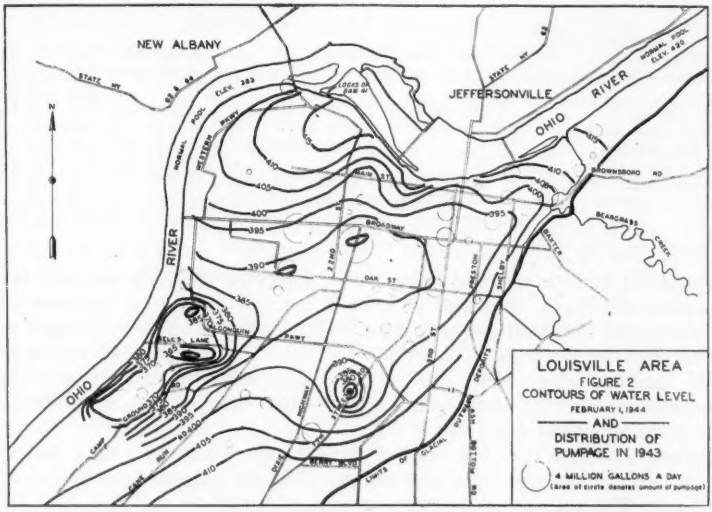

FIG. 2. Map of the Louisville area showing contours of water level, February 1, 1944, and distribution of pumpage in 1943.

part of the area has been commenced by rubber industries since the war began. Several distilleries, whose pumpage has also been increased as a result of the war, are located directly east of these rubber industries.

Although, for convenience, the pumpage is given in the table and on the map as the average daily pumpage for the 365 days of a year, the average daily pumpage during summer months is about 20 to 30 per cent higher than the average daily pumpage during winter months. The increase in pumpage during summer months is most pronounced where the water is used for air-conditioning and ice-making.

Yields of individual wells constructed during the last few years have ranged from a few gallons a minute to more than 3,000 gallons a minute. Specific capacities (gallons a minute per foot of drawdown of water level after several hours of pumping) recorded for 70 industrial wells ranged from 8 to 410, and average about 60. Because the yield of a well is dependent on

TABLE 1.
ESTIMATED AVERAGE DAILY PUMPAGE FROM WELLS IN LOUISVILLE AREA, BY INDUSTRIES
(Million gallons a day).

	No. of plants, 1944	No. of wells, 1944	1937	1938	1939	1940	1941	1942	1943	1944	Aug. 1943	Jan. 1944
Distilling	14	42	6.2	6.1	6.5	10.5	14.9	16.7	17.2	10.4	17.0	16.3
Rubber manufacturing	6	39	—	—	—	—	0.2	4.6	17.0	19.9	26.9	21.8
Metal working	15	27	1.6	1.6	1.6	1.6	3.3	3.8	3.9	3.7	4.3	3.7
Oil refining	5	13	4.9	4.9	4.9	4.7	4.6	4.6	3.9	4.2	4.1	3.8
Brewing	3	9	5.3	5.6	5.3	5.2	4.1	4.1	3.8	3.6	3.8	2.9
Air conditioning, refrigerating	93	103	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	8.3	1.0
Ice-making, cold storage	9	20	4.1	4.1	4.1	4.2	3.6	3.2	2.9	2.9	5.1	1.1
Dairying	14	21	2.2	2.2	2.2	2.2	2.2	2.3	2.3	2.2	2.4	2.1
Meat packing	10	21	2.4	2.4	2.3	2.2	2.2	2.1	2.0	2.1	2.0	1.9
Tobacco processing	4	10	2.5	2.6	2.5	2.2	1.9	1.7	1.2	0.9	1.7	1.0
Gas and electricity	2	5	0.8	0.9	0.8	0.8	0.8	0.8	0.9	0.8	0.3	1.7
Food manufacturing	14	18	0.7	1.0	1.5	1.3	1.2	1.1	0.8	0.7	1.0	0.5
Miscellaneous	20	24	1.9	1.9	2.0	2.4	2.6	2.0	1.9	1.9	2.1	1.6
	209	352	36.6	37.3	37.6	41.2	45.4	50.8	61.5	57.0	79.0	59.4

the depth of water in the sand and gravel, and because the heavy pumpage has decreased this depth, the yields of wells in the area have been decreased by an average of about 50 per cent since 1939. This has caused shortages of water in many localities. These shortages have been especially serious in those localities where wells were already distributed to obtain nearly the maximum amounts of water available and where new wells have produced only small additional quantities of water.

Water Levels.—The 1937 flood of the Ohio River covered a large part of the valley, and recharge from it practically filled the ground-water reservoir. At Louisville basements and sewers remained flooded by the ground water for some time after the river receded, and as a result many "dewatering" pumps were operated heavily and natural springs along the river were developed to assist in the rapid lowering of the water table. Southwest of Louisville the flood raised the water table to the highest level in years, though not as high as it raised the water table in Louisville. During the spring and summer of 1937 the water table throughout the area declined rapidly as the excess water was pumped out or seeped out naturally into the river. Since then, no major floods having occurred, the water table has been controlled mainly by the pumpage and has continued to decline as a result of the increase in the pumpage for war plants.

The decline has been lightest in northeast Louisville, one observation well showing a net decline of only about five feet since 1938. The pumpage has not been increased in this locality, however, and the well is near Beargrass Creek and only about ½ mile from the river, both of which probably recharge the ground-water reservoir.

In downtown Louisville, just west of 3rd Street between Main and Broadway, the water levels in observation wells have had a net decline of

about four or five feet each year since 1938. During 1938 and 1939 at least a part of this decline probably was caused by the recharge from the flood still moving away from this locality toward the river's lower pool to the southwest, but since 1939 the decline has been largely caused by increased pumping in south and west Louisville. These downtown wells show a seasonal fluctuation of water levels of several feet, caused principally by the nearby seasonal pumpage for air-conditioning of theatres and business places.

In west, south, and south-southwest Louisville and just outside the city limits, where most of the distilleries are located, water levels in observation wells declined very little during 1938 and 1939, but since 1939 they have declined steadily at rates of four to six feet a year. In the spring of 1944 the water levels around the Seagram and National distilleries were raised by stopping nearly all the pumpage and by artificially recharging the underground reservoir, but this was only a local occurrence and is described later in this paper.

Southwest of Louisville where the rubber manufacturing plants have been constructed during the past three years, the water levels in observation wells did not decline much until the summer of 1942, when they started a precipitous decline as a result of the heavy pumping for the rubber plants. This precipitous decline has continued at rates between 8 and 15 feet a year, the rates being greatest in those observation wells nearest to the heavy pumping.

Fig. 4 shows the hydrographs of three wells near distilleries just south of the Louisville city limits. These hydrographs indicate the decline of water levels in that locality since 1941. More particularly, however, they show the effects of the conservation and artificial recharge during the spring of 1944.

Fig. 2 is a contour map of the water table on February 1, 1944. It shows the several steep cones of depression in the water table caused by concentrated pumping, and the direction of the movement of the water. The map for February 1, 1945, has not yet been prepared, but it will show in general the same steep cones of depression, with the water levels in most places being several feet lower than they were in 1944.

Withdrawals from Storage and Natural Recharge.—In former years, inflow of water from joints in the limestone bedrock and percolation from rainfall kept the sand and gravel in the valley nearly full of water, with considerable overflow spilling into the river. During recent years, however, nearly all of this recharge has been withdrawn through wells, with very little spilling into the river. In fact, a large amount of water is now being drawn into the sand and gravel from the river. Also, in order to supply the heavy demand on wells, it has been necessary to draw additional water from storage by lowering the water level in the sand and gravel. The water level has now been drawn down so that only about the lower half of the sand and gravel in the deeper parts of the old valley contains water. In some localities of extremely heavy pumping, only a few feet of water remain above the bedrock.

Rough computations have been made of the volume of sand and gravel that has been dewatered during each of the past several years. Using the

results of these computations and estimating the effective porosity of the sand and gravel at about 20 per cent, it is estimated that the water withdrawn from storage increased from an amount between 5 and 10 million gallons a day in 1938 to an amount between 20 and 30 million gallons a day in 1943. For 1938 this leaves from 27 to 32 million gallons a day of the pumpage that was supplied by natural recharge to the underground reservoir, and for 1943 it leaves from 32 to 42 million gallons a day of the pumpage that was supplied by natural recharge. Independent computations of the recharge in 1943, based on estimated rates of flow from the bedrock and from the river, with a reasonable allowance for direct percolation from rainfall, indicate that the recharge is somewhat less than 40 million gallons a day. By far the greater part of this recharge comes from the joints and crevices in the limestone on the eastern side of the old channel in the bedrock and from the river to the west. It is estimated that probably less than 1/10 of the recharge comes from rainfall on the land surface of the valley itself.

As water has been pumped from storage, steeper hydraulic gradients have been developed in the water table which have caused water to flow at increased rates from the localities of recharge to the localities of heavy pumping. However, the rate of recharge has not been increased as rapidly as the rate of pumping, and hence water has been drawn from storage in increasing amounts. Because of the small remaining depth of water in the underground reservoir, which prohibits much further steepening of the hydraulic gradients, it is believed that the natural recharge to the present developments is now about at its maximum. It has therefore been recommended that the net pumpage from these developments be reduced to and held at about 40 million gallons a day. The pumpage should be reduced most in those localities of heavy withdrawal where the water levels are declining most rapidly and where the depth of water is small, namely, those localities including the distilleries to the south and the rubber plants to the southwest of Louisville.

Possibilities of Obtaining Supplemental Ground-water Supplies.—In order to make the necessary reduction in pumpage, many of the industries are installing conservation equipment such as cooling towers and refrigeration, and are using as much city water as possible in place of ground water. However, indications are that these conservation measures will not entirely eliminate the need for overpumping. Ground water is too much in demand because of its uniformly low temperature the year round and because it is still much cheaper than surface water in many places. Therefore, some industries are either planning or are already developing supplemental supplies of ground water. It appears likely that these and other supplemental supplies will be very important to the industrial growth of the Louisville area.

The methods which appear to be most favorable for obtaining additional ground-water supplies are (1) development of the glacial outwash deposits in the rural areas along the Ohio River southwest and northeast of the Louisville area; (2) increase in induced infiltration from the Ohio River into the ground-water reservoir; and (3) artificial recharge of the reservoir through wells or basins.

(1) Large amounts of water are probably in storage in the glacial outwash

deposits in the rural areas to the southwest and northeast of the Louisville area. The deposits are constantly recharged by rainfall and by percolation from the adjoining rocks, and are discharging water through springs and seeps along the banks of the river. Water can be drawn from storage in the deposits, and the water that is now being discharged can probably be intercepted by wells before it spills into the river. In addition, the heavy pumping of wells to intercept this natural discharge will lower the water table so that additional large quantities of water will probably flow into the sand and gravel deposits from the river. An intensive program of test drilling and observation is now under way in each of these two rural areas to determine more accurately how much ground water can be obtained from wells there.

(2) Induced infiltration from the river is accomplished by pumping wells near the river along those reaches where the sand and gravel of the ground-water reservoir crops out in the river bed. When the water table is lowered next to the river as a result of the pumping, a steep hydraulic gradient is produced from the river to the wells, causing a large part of the yield of the wells to be drawn from the river. The amount of water that can be obtained by this method is determined principally by the area of sand and gravel that crops out in the river bed and by the permeability and thickness of the sand and gravel between the river bed and the wells. Conditions appear to be favorable along the river from about 3rd Street northeastward and from a short distance above Bells Lane southwestward. The closer the wells are to the river, the steeper are the gradients that can be produced from the river to the wells and the greater are the quantities of water obtained. As previously stated, a large part of the recharge to the present well fields in the Louisville area is drawn into the ground-water reservoir from the river. This is an application of the induced-infiltration method of obtaining water, although most of the wells are considerable distances from the river with the result that the gradients from the river to the wells are not very steep. By relocating some of the wells closer to the river the gradients could be steepened and the recharge increased. In the rural areas to the southwest and northeast of the Louisville area, this method of obtaining water would be a part, probably a major one, of the general overall plan of developing the glacial outwash deposits. Detailed studies are now being made of the induced infiltration in the Louisville area, and of the possibilities of increasing it. One large industry has already completed a program of test drilling and pumping tests, and has constructed a collector well on the river bank to take advantage of the favorable conditions found for induced infiltration at that site.

(3) The underground reservoir at Louisville is particularly suited to receive artificial recharge. The water level has been drawn down so that even in the deeper parts of the old valley only about the lower half of the sand and gravel contains water, and the reservoir therefore can hold considerably more water than it now holds. Also, since natural recharge is entering the reservoir from nearly all directions, almost no water flows out of it. And, finally, more water is being pumped from wells than is entering the reservoir. These conditions insure that any water that is artificially recharged to the reservoir will be recovered, at least up to an amount equal to the deficiency

in natural recharge. In some localities it will be recovered in greater amounts than the local deficiencies.

Artificial recharge can be accomplished either by introducing clear water into the reservoir through wells, or by applying clear or turbid water to recharge basins. Although recharge through wells can be practiced with ground water that has been used for cooling purposes, as is now being done on Long Island, New York, on a large scale, this method has the disadvantage that the recharge water is warm and tends ultimately to raise the temperature of the water in the reservoir. The same statement applies to recharge with filtered river water which first is used for cooling. Recharge through wells in the Louisville area can probably be best accomplished with filtered river water which is not first used for cooling. Since the average temperature of the river water throughout the year is about the same as the temperature of the ground water, the net effect on the temperature of the water in the reservoir is negligible if equal amounts of river water are introduced in the winter and in the summer. The use of river water only in the winter when it is cold is especially advantageous for it tends to lower the temperature of the water in the reservoir. Water introduced into wells should be clear and free of bacterial and other organic matter, both for sanitary reasons and to prevent clogging of the wells. City water, which has been both filtered and chlorinated, is especially advantageous for this use. Water can be introduced during the winter into the same wells which are pumped during the summer. By this procedure, most of the material in the recharge water which tends to clog the wells should be removed by pumping during the summer. Several industries are now recharging the reservoir through wells with ground water that is first used for cooling, and one industry is recharging with cold city water directly out of the mains. Altogether, the quantity of water recharged averages about two million gallons a day.

A recharge basin may be formed in the Louisville area by removing the relatively impermeable surface materials from the glacial outwash deposits. These surface materials in general range from 5 to 30 feet in thickness. Recharge through such a basin probably can be accomplished most economically by the use of raw river water, a procedure which has been practiced successfully in several parts of the United States. The sand and gravel between the bottom of a basin and the water table would be analogous to a slow sand filter such as is used in many water treatment plants. The suspended matter in the water would be removed within a few inches as the water would percolate down from the bottom of the basin. The bacterial contamination in the water might be carried farther but would probably be entirely dissipated before it moved very far from the basin. For best operation of a basin the water probably should be pre-settled when it is highly turbid. The bottom of the basin would need scraping at intervals, depending on the turbidity of water introduced. An experiment with a small basin has been planned for the Louisville area, but, because of the apparent high cost of this method, the experiment probably will not be carried out for some time unless other methods of increasing the ground-water supply prove to be less feasible than anticipated.

ARTIFICIAL RECHARGE WITH CITY WATER AT SEAGRAM AND NATIONAL DISTILLERIES

Because of the declining water level, the yields of wells supplying the Joseph E. Seagram and Sons, the Dant and Dant of Kentucky, and the National Distillers Corporation distilleries on Seventh Street Road and Bernheim Lane (Fig. 3) had decreased so much by the spring of 1944 that the

FIGURE 3

MAP SHOWING LOCATION OF OBSERVATION WELLS AND WELLS SUPPLYING NATIONAL, SEAGRAM, AND DANT AND DANT DISTILLERIES.

SCALE 0 1000 4000 FEET

demands of the plants for water were not quite being met from the wells. Instead, some city water was being bought to make up for the lack of ground water. Furthermore, it was estimated by the plant engineers and by the Geological Survey that by the coming summer the total yield of the wells at all three plants would decline from about 4,400 gallons a minute to between 3,000 and 3,400 gallons a minute. This would mean that there would be a shortage of ground water during the summer of between 1,000 and 1,400 gallons a minute. Since the distilleries needed the water mostly for cooling, and since the ground water has a more or less constant temperature of 57° F.

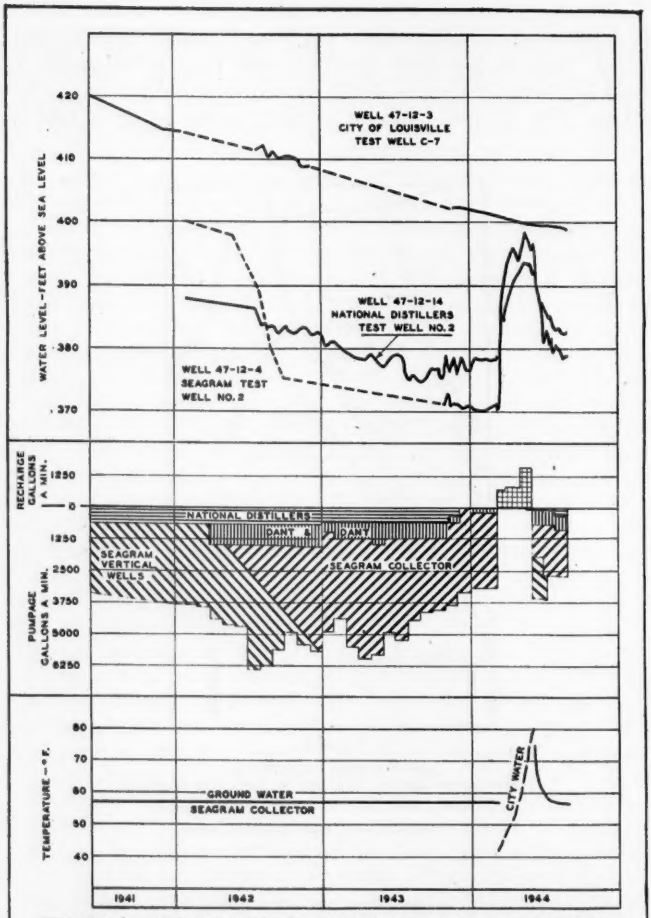

FIGURE 4—HYDROGRAPHS OF TYPICAL WELLS—PUMPAGE FROM, AND RECHARGE TO WELLS IN VICINITY OF SEAGRAM, DANT & DANT AND NATIONAL DISTILLERS PLANTS.

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whereas the city water usually reaches 85° during summers, it was clear that some corrective measures were necessary if the plants were to be kept in full production during the summer of 1944.

Mr. Frederick H. Weed, Regional Engineer of the War Production Board, urged the plants to carry out a suggestion previously made by Dr. O. E. Meinzer, U. S. Geological Survey, to use city water and let the wells rest during cold weather, thus allowing the water table to recover, and to artificially recharge the reservoir with more of the cold city water in order to raise the water table even higher. This would partly fill the local cone of depression in the water table and would make it possible to pump the wells at a higher rate during the coming summer. It was computed by the Geological Survey that, if pumping of the wells were stopped and artificial recharge of about 1,000 gallons a minute were practiced for the remainder of the spring, or as long as the temperature of the city water would remain below 60° F., the water level would be raised enough so that about 4,000 gallons a minute could be pumped from the wells during the summer.

On March 10, 1944, pumping from all the wells at the three plants was stopped, and recharging with city water was commenced on a small scale through two vertical wells at the National Distillers plant and on a much larger scale through the Seagram collector well.

Early in May the actual rise of the water level caused by shutting down the wells and recharging through them was observed to be very close to the rise that had been computed by the Geological Survey, indicating that the assumptions made in the computations regarding permeability and effective porosity of the sand and gravel were essentially correct. These assumptions were that the average permeability is equal to 2,500 Meinzer units and the average effective porosity is 20 per cent. This being so, it was reasonable to expect that the rest of the original computations based on these assumptions would also prove to be fairly dependable—that the plants would be able to pump about 4,000 gallons a minute of ground water for the remainder of the summer if the recharge were stopped and pumping from the wells begun again about the middle of May.

However, estimates of the demand for ground water still remained at 4,400 gallons a minute, and the check in the computations made it appear more certain that this demand would not be met. Therefore, Mr. Weed again talked with the plants' officials, who agreed to make several changes in the plants so that they could use water with a higher temperature than was formerly possible. City water was, therefore, continued in use at the Seagram and Dant and Dant plants until June 3, even though by this time its temperature had reached nearly 80° F. Pumping was started again from some of the National Distillers wells on May 17. During the summer a mixture of city water and ground water was used at all three plants so that the groundwater pumpage was as small as possible.

Fig. 4 shows a graph of the rate of pumping from the wells prior to March 10, the rate of recharge during the spring, and the rate of pumping during the summer. It also shows graphs of water levels in typical observation wells, and graphs of the temperature of the ground water from the Seagram collector

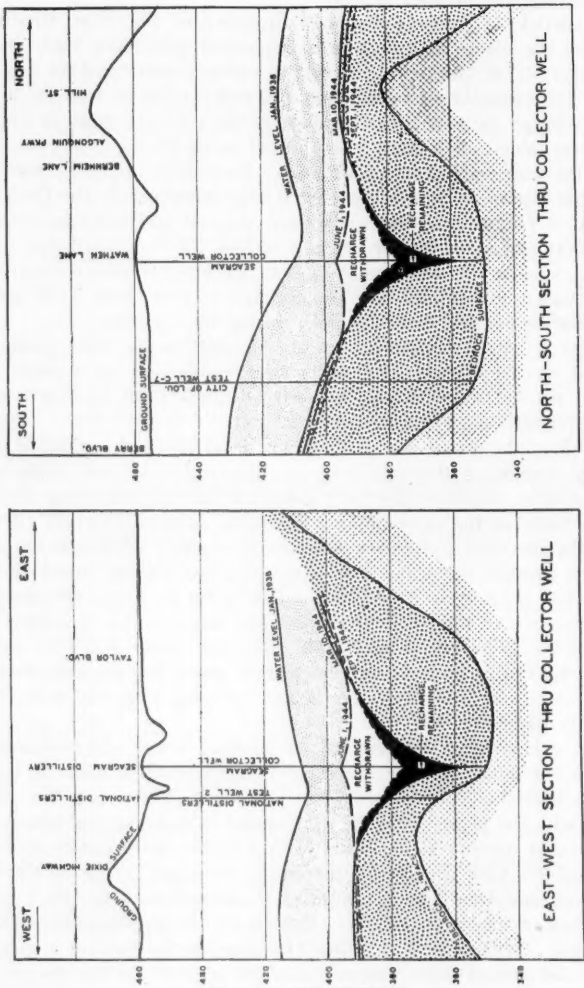

FIGURE 5. GEOLOGIC SECTIONS SHOWING ANCIENT RIVER CHANNEL AND WATER LEVELS IN GLACIAL OUTWASH
Horizontal Scale 0 2000 4000 Feet

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well before recharging, the temperature of the city water recharged, and the temperature of water from the collector well after recharging.

So effective were the ground-water conservation measures practiced at these plants that the total demand during the summer averaged only about 3,000 gallons a minute instead of the 4,400 gallons a minute originally estimated. As a result the plants had a reserve of cold ground water at all times during the summer, and the wells could be pumped at considerably higher than average rates for short periods of time.

Fig. 5 shows two cross-sections through the Seagram collector well, giving the position of the land surface and bedrock, and the elevations of the water level in the sand and gravel on March 10, June 1, and September 1. It shows how the cone of depression was filled during the spring and how much of the recharged water was withdrawn during the summer. It also shows how the areal decline of the water table outside of the local cone of depression continued.

Since the fall of 1944, the National distillery has installed a cooling tower and refrigeration, and it will no longer use its wells, even during the summers. However, although the Seagram and Dant and Dant distilleries have also installed cooling towers and made various other changes in their water systems, they are still largely dependent on ground water during the summers. Inasmuch as the decline of water levels in the Louisville area is continuing, with resulting decreasing yields of wells, the officials of these two plants are continuing the procedure started in 1944, of using city water in the plants and artificially recharging the ground-water reservoir with additional cold city water during the winters and of pumping the wells only during the summers. This is not only helping to eliminate the water shortage in the Louisville area as a whole, but will allow cold water to be pumped from the wells at the two plants at much greater rates during the summers than otherwise would be possible. Other industries in the Louisville area might well consider this method of increasing their supplies of cold water during the summers.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
Feb. 25, 1946.

BIBLIOGRAPHY.

(1) Butts, Charles: The geology and mineral resources of Jefferson County, Kentucky. Kentucky Geological Survey, Series IV, Volume III, Part II, 1915.
(2) Caye, Woolsey M.: Ground water—well report. Commissioners of Sewerage of Louisville, typewritten, 1939.
(3) Jefferson County Health Department: The real property and sanitary Survey of Jefferson County, Kentucky, 1939–1940. Fiscal Court of Jefferson County, 1940.
(4) Johnson, C. Frank: Final report of Commissioners of Sewerage of Louisville, 1919–1942, pp. 370–387. Commissioners of Sewerage of Louisville, 1943.
(5) Diehl, Robert B.: The diminishing supply and conservation of the underground water supply of Louisville, Kentucky. Diehl Pump and Supply Company, 1943.
(6) Wenger, H. V.: Report on the ground water supply, Louisville, Kentucky. Water Division, Office of War Utilities, typewritten (restricted), 1943.
(7) Guyton, W. F., Stuart, W. T., and Maxey, G. B.: Progress report on the ground-water resources of the Louisville area, Kentucky. U. S. Geological Survey, mimeographed, March, 1944.
(8) Stuart, W. T.: The ground-water investigation at Louisville, Kentucky. The Kentucky Engineer, Vol. VI, No. 3, pp. 18–22, May, 1944.

(9) Maxey, G. B.: Data obtained from tests for infiltration from Ohio River at Bells Lane, Louisville, Kentucky. Kentucky Department of Mines and Minerals, blue-printed, June, 1944.
(10) Stuart, W. T.: Conservation of ground water, including artificial recharge, by two companies in the Louisville area, Kentucky. Kentucky Department of Mines and Minerals, mimeographed, July, 1944. (Also Cast Iron Pipe News, pp. 2–4, January, 1945.)
(11) Hamilton, D. K.: Ground water in the bedrock beneath the glacial outwash in the Louisville area, Kentucky. Kentucky Department of Mines and Minerals, mimeographed, August, 1944.
(12) Guyton, W. F., and Sublett, H. E.: Conservation of ground water in the Louisville area, Kentucky. Kentucky Department of Mines and Minerals, mimeographed, October, 1944.
(13) Chemical analyses of water from wells in the Louisville area, Kentucky. Kentucky Department of Mines and Minerals, mimeographed, November, 1944.
(14) Graphs of water levels in wells in the Louisville area, Kentucky. Kentucky Department of Mines and Minerals, blue-printed, November, 1944.
(15) McNamee, R. L., and Porter, S. D.: Report on water resources for the Underground Water Users Association, Louisville, Kentucky. Shoecraft, Drury, and McNamee, Consulting Engineers, mimeographed, November, 1944.
(16) Guyton, W. F.: Depleted wells at Louisville recharged with city water. Water Works Engineering, Vol. 98, No. 1, pp. 18–20, January, 1945.
(17) Drillers' logs of wells and test borings in the Louisville area, Kentucky. Kentucky Department of Mines and Minerals, mimeographed, January, 1945.
(18) Sublett, Hazel E.: Chemical quality of ground water in the Louisville area, Kentucky. Kentucky Department of Mines and Minerals, mimeographed, April, 1945.

SYNTHETIC REPLACEMENTS AS AN AID TO ORE-GENETIC STUDIES.

C. SCHOUTEN.

FOREWORD.

Before the war in this journal the results of many experiments on synthetic replacements were described.[1] These experiments were carried out with the object of obtaining data on criteria for replacement structures observed in polished sections.

One of the most striking features of these results was the close similarity of synthetically obtained structures with those occurring in nature.

The following notes give some results of this mode of research in diagnosing the mode of origin of ore deposits as applied to the investigation of certain pyritic ore bodies.

During ore microscopic studies it struck the writer that copper, lead and zinc sulphides in abundance may be pseudomorphic after original FeS_2 forms [2] whereby the internal structures generally are strikingly preserved. The FeS_2 exhibits a great variety of forms in different ore deposits. In each single deposit, however, these forms are more or less characteristic for the deposit in question.

The observation that several sulphides were seemingly pseudomorphous after FeS_2 offered promise that synthetic replacement of the original FeS_2 might retrace the process that probably took place in nature. The outcome of these experiments is unusual enough to warrant their description.

The results obviously give information concerning the nature of the process.

I am well aware that laboratory experiments carried out in concentrated solutions of perhaps fantastic composition cannot be compared with the natural succession of events. Moreover, in nature the final result may be similar to one obtained in the laboratory, although the progress in both cases may have been quite different. On the other hand, experimental results are convincing proofs of possibilities as to the mode of formation, and if a supposed mode of origin may easily be reproduced, it at least gives supporting evidence.

COMPARISON OF NATURAL AND SYNTHETIC EXAMPLES.

Examples from Mt. Isa Ores.—The results of microscopic studies of the unusual stratified ores of Mount Isa, Australia, were described in two earlier publications.[3] Real pseudomorphs after perfectly formed idiomorphic crystals of pyrite were abundantly observed. In those ores no doubt existed as to the true origin. Many structures, however, were ascribed to metasomatism in the publications mentioned, which had previously been regarded as such. I refer particularly to the atoll-shaped bodies of various forms [4] which occur

[1] C. Schouten, Econ. Geol., 1934, XXIX, pp. 611–658.
[2] Econ. Geol., 1946, XLI, p. 348.
[3] H. F. Grondijs and C. Schouten, Econ. Geol., 1937, XXII, pp. 407–450.
C. Schouten, Some Notes on Micro-Pseudomorphism, Econ. Geol., 1946, XLI, p. 348.
[4] C. Schouten, Some Notes on Micro-Pseudomorphism, Econ. Geol., 1946, XLI, p. 357.

abundantly in some layers and are absent in others. These "atolls," it is true, were observed in the oxidized ores as well. Hence, preservation of such structures is proved. Nevertheless synthetic experiments were carried out on layers rich in pyrite free from other sulphides and supposed to be the "guest-layers" for such "atolls" The results were astonishing with respect to the similarity with natural structures. To demonstrate this it seems desirable to give some details of the original pyrite forms.

In a few layers only idiomorphic pyrite crystals of about .010–.020 mm occur, which in part show inclusions of sulphides with curious outlines (Figs. 37, 39). In some cases these inclusions occupy almost the whole crystal

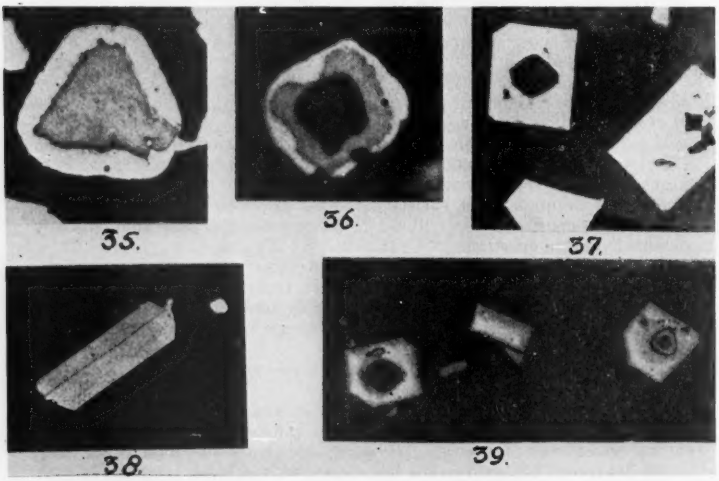


FIG. 35. Galena (faint grayish white) has replaced the kernel of a pyrite crystal. Dark gray sphalerite. × 2,000. Mount Isa.

FIG. 36. Same as Fig. 35. Kernel replaced by sphalerite (black) and galena (faint gray). × 2,000. Mount Isa.

FIG. 37. Same as Figs. 35 and 36. Kernels replaced by sphalerite. Matrix, sphalerite (gray) with a lath of chlorite (black). × 1,000. Mount Isa.

FIG. 38. Idiomorphic lath of pyrrhotite (faint gray), one-half replaced by galena (whiter than pyrrhotite) in groundmass of carbonate (black). × 600. Mount Isa.

FIG. 39. Same as Figs. 35, 36 and 37. × 680.

leaving no more than a bordering rim of pyrite. That these remarkable structures are really the result of selective replacement has been dealt with elsewhere.[5] Synthetic replacement of pyrite crystals of the same locality gave rise to the formation of absolutely comparable structures (Figs. 106, 107).

In other layers "atolls" with irregular outlines [5] are common. If experi-

[5] See Fig. 23, ECON. GEOL., 1946, XLI, p. 356.

ments are made on unimpaired pyrite units from such layers, atolls are produced of the same sort as the natural ones (Figs. 108, 94, 95).

In some cases the pyrite of the Mount Isa ores shows replacement by pyrrhotite, a few pyrite remnants along the outlines being preserved (Fig. 93). Original pyrite of the same sort after chemical treatment in the laboratory gave identical structures (Fig. 92). Idiomorphic pyrite crystals from this ore that had special crystal zones replaced adjacent to crosscutting veinlets, gave identical structures in the comparable zones after synthetic replacement of similar crystals. These few examples of Mount Isa will serve, although they could be extended by many others.

Rammelsberg and Meggen.—In Rammelsberg and Meggen the original FeS_2 forms are of a distinct character. They commonly show intergrowths of pyrite and marcasite and the latter is much more susceptible to hydrothermal solutions than the pyrite. The replacement phenomena have been described elsewhere.[6] If fresh intergrowths of both sulphides from Rammelsberg or Upper Silesia are treated with copper solutions, the results (Plate 3) [6a] are clearly similar to those known from the original deposits (Plate 2).[6b] It is always the marcasite that has been selectively replaced.

Mansfeld Examples.—Several structures from the ores of Mansfeld were ascribed to replacement phenomena of pyrite by various copper or copper-iron sulphides.[7] Examples were given particularly of small pyrite spheres composed of tightly packed crystals in several stages of metasomatism. One of the forms attracting special attention was bornite or chalcocite spheres with a few impaired pyrite crystals left in the center and bordered by a rim of unattacked crystals. These bodies could also be obtained synthetically using fresh spheres from the same locality.

In other instances this outer rim of crystals had not been selectively preserved in nature; on the contrary, all small crystals of the spheres without exception have been more or less attacked, giving rise to the formation of a sphere composed of loosely packed and impaired grains.[8] When fresh spheres of this class were treated with copper solutions exactly similar structures resulted (Fig. 104).

In my opinion all these examples seem to indicate convincingly that the natural structures described above are really due to replacement, although some German investigators attach little importance to these similarities.

Some more normal and more familiar examples may be added.

Other Examples.—In ores of Cobalt, Ontario, curiously formed and very well-known cross-like or dendritic figures of Co-Ni arsenides in native silver occur. The silver has been shown by several investigators to be obviously younger than, and to have partly replaced, the arsenides,[9] If fresh Co-Ni

[6] C. Schouten, Some Notes on Micro-Pseudomorphism, ECON. GEOL., 1946, XLI, pp. 362, 372.

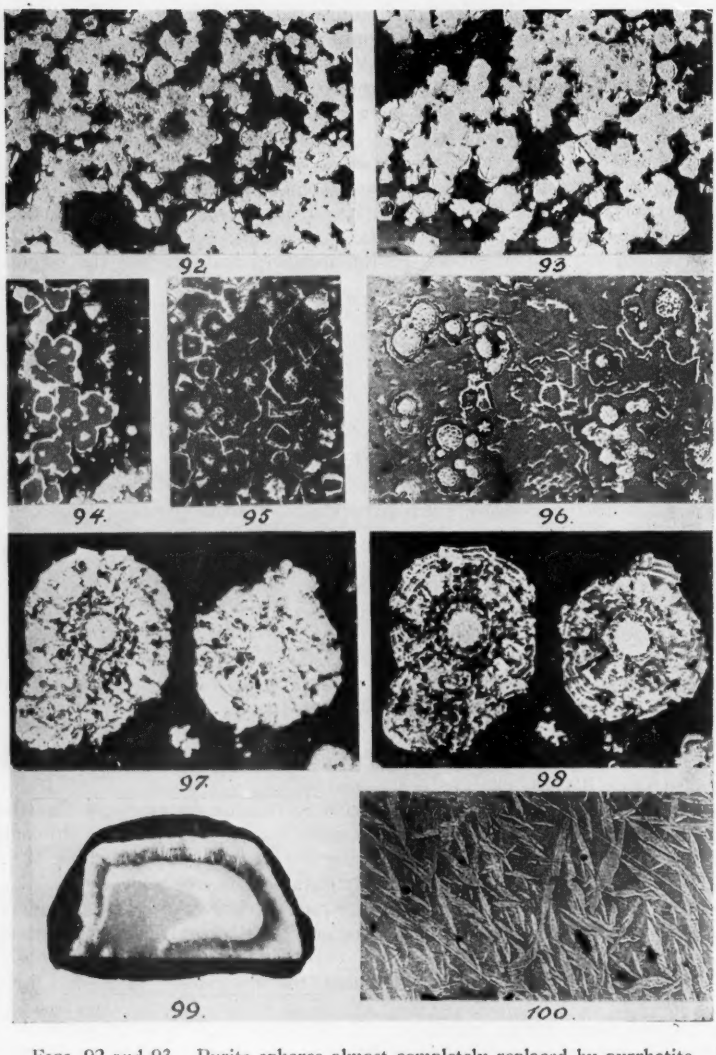
[6a] See Pl. 3, ECON. GEOL., 1946, XLI, p. 364.

[6b] See Pl. 2, ECON. GEOL., 1946, XLI, p. 363.

[7] *E.g.*, R. W. Van der Veen, Mineragraphy and Ore-Deposition (G. Naeff, The Hague, 1925).

[8] See Figs. 70, 80, 82 in ECON. GEOL., 1946, XLI, pp. 378, 380.

[9] *E.g.*, R. W. Van der Veen, Mineragraphy and Ore Deposition, *op. cit.*
E. S. Bastin, ECON. GEOL., 1917, XII, p. 219.



FIGS. 92 and 93. Pyrite spheres almost completely replaced by pyrrhotite. In shale (black); pyrrhotite, gray; pyrite remnants, white. Mount Isa. × 240. FIG. 92. *Synthetic* replacement of massive Mount-Isa pyrite. FIG. 93. Natural structure.

FIG. 94. Curious "atoll" forms. Kernels of sphalerite (gray) with pyrite rim and pyrite point in center (white). Black, shale. Mount Isa. × 400.

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arsenides of the same locality are exposed to a concentrated silver solution, remnants of arsenides appear with strikingly similar forms to those reported from the original ores (Fig. 101). In other ores of the same type, native silver is almost always bordered by rims of arsenides, which have been regarded as relics. This structure is also clearly developed through synthetic metasomatism.[10]

In the sulphide enrichment zone of many copper ore deposits familiar examples of replacement of pyrite by bornite or chalcocite are known. These well known structures are easily obtained synthetically (Figs. 102, 103).

The unmistakable metasomatic structures of pyrite replaced by chalcopyrite from Bisbee, Ariz. (Fig. 103), the textbook examples of sphalerite by chalcocite from Tsumeb, S.W. Africa, of cuprite by copper from Bisbee, Ariz.,[11] of pyrite by bornite from Butte, Mont., and others could be absolutely imitated by hosts of the same localities if exposed in the laboratory to solutions of the necessary composition.

Two or more different sulphides may be simultaneously precipitated with colloform structures; on some cases these intergrowths indicate metasomatism. This sort of replacement structure is well-known in supergene and also in hypogene deposits. In "Metasomatische Probleme."[12] I presented other possibilities concerning the mode of origin of such kinds of intergrowths and stated that their existence is not at all convincing for simultaneous marine deposition as postulated by some German investigators. That colloform structures may be delicately preserved through metasomatism hardly needs confirmation. Accordingly, this can be proved by synthetic experiments as will be shown by some examples.

Synthetic Examples.—Reaction of copper solutions on fresh pyrite from Rammelsberg produced structures illustrated in Figs. 96, 97 and 98, which imitate exactly—but nevertheless wrongly—simultaneous gel deposition. Not

[10] ECON. GEOL., XXIX, 1934, p. 636, Fig. 29.
[11] ECON. GEOL., XXIX, 1934, pp. 633, 645, Figs. 19, 38.
[12] C. Schouten, Metasomatische Probleme, 1937.

FIG. 95. Massive Mount Isa pyrite (white) synthetically replaced by chalcocite (gray) in shale (black). Compare with the natural forms of Fig. 94. × 400.

FIG. 96. Massive pyrite (white) from Rammelsberg (Germany) synthetically replaced by bornite (gray). Only pyrite spheres and rims are left. Structure seems to indicate (wrongly) simultaneous gel-deposition of pyrite and bornite. × 500.

FIGS. 97 and 98. Two pyrite concretions composed of a pyrite sphere surrounded by concentric pyrite zones (white) in schist (black). FIG. 97. The original concretions from Rammelsberg, Germany. FIG. 98. The same concretions after partial synthetic replacement by chalcocite (gray) as transitional stage to complete pseudomorphism. The structure similates simultaneous gel-deposition of pyrite and chalcocite. × 400.

FIG. 99. Gypsum (light gray kernel) has been partially and synthetically replaced by anglesite (crystalline rim). Between the remnants of gypsum and the anglesite an elongated "vug." Natural size.

FIG. 100. Stromeyerite with oleander-leaf structure obtained by synthetic replacement of chalcocite in a silver solution. Etched.

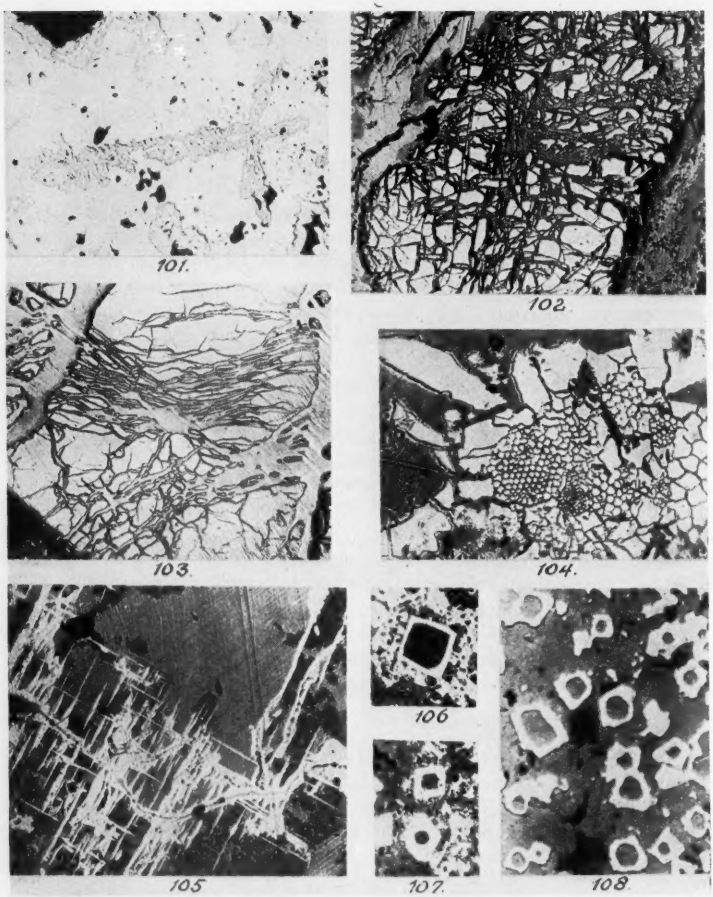

FIG. 101. Synthetic replacement of massive Co-Ni arsenides from Cobalt, Ontario, by silver. Curious cross-like remnant of arsenide (faint gray) in silver (white). Very similar to the well-known remnants in the original ore. × 55.

FIG. 102. Pyrite grain (white) from Siegen (Germany) synthetically and partially replaced by bornite (gray) and chalcocite (somewhat lighter). Completely similar to natural intergrowths of this locality.

FIG. 103. Massive pyrite (white with relief) from Bisbee synthetically and partially replaced by chalcopyrite (faint grayish). Completely similar to the well-known natural structures.

FIG. 104. Synthetic replacement of FeS_2 forms (white) from the "Dachklotz" of the copper shale (Germany) by chalcocite (light gray). Compare with the natural structures of Figs. 80 and 82 from the same locality. × 200.

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less convincing is the result shown in Fig. 110. Here even "dessication-cracks" and "dusty intergrowths" seem to prove simultaneity. Nevertheless, it is known with certainty that only original structures of the pyrite can have been preserved.

Elongated inclusions of pyrite occur in many pyritic ore bodies. One of the tips of such lenses, which might be named the "tail-side," commonly shows much finer grained pyrite than that of the main lense. Younger sulphides or other minerals are commonly concentrated at these tail-sides. After treatment of such pyrite lenses with copper solutions, for example, the selective replacement of the finer grained pyrite in such areas becomes apparent.

Concentric shaly original structures of pyrite, marcasite or melnikovite may be delicately preserved by synthetic replacement, the result being selective attack of the melnikovite and marcasite zones with the pyrite zones unreplaced. Similar structures may be preserved [18] in the alteration of zonally built pyrite crystals. Many other examples could be given.

In other words, it can be established experimentally that if natural host-guest contacts of undoubted replacement origin which show remnants with tongues, embayments or caries, replacement along heterogeneous contacts or cleavage planes, or zonal, colloform or graphic intergrowths, as the dominant relationships, synthetic replacements of the same hosts give exactly comparable results.

The following conclusion may, therefore, be stated:

If ore structures in polished surfaces of natural specimens are granted to be due to metasomatism it is possible to produce similar structures synthetically if comparable hosts from the same localities are submitted to the necessary chemical treatment;

and inversely:

If synthetic replacement of fresh material from a certain ore body shows structures identical to those observed in the original ore, which are supposed to be metasomatic, it may be concluded that these natural structures are also metasomatic.

It seems incredible that all of the above mentioned examples and many others, would be due to accidental circumstances.

Some notes about curiosities in the mode of progress of metasomatism may be added.

[18] Econ. Geol., 1934, XXIX, p. 637, Figs. 23, 26.

Fig. 105. Synthetic replacement of bornite (gray) by chalcopyrite (white) and covellite (dark gray). Very similar to well known natural structures.

Figs. 106 and 107. Synthetically produced atolls. Gray, chalcocite; white, pyrite. These results were obtained originating with massive pyrite from Mount Isa where similar atolls exist in the original ore. See *e.g.* Figs. 37 and 39.

Fig. 108. Synthetic replacement of massive pyrite bed from Mount Isa by chalcocite (gray). Pyrite remnants (white) show atoll form as in the original ore. Compare with Figs. 23 and 25.

If a silver nitrate solution reacts on a polished specimen of chalcocite, this is replaced in three stages. After treatment, from the polished surface inward, three zones may be observed, viz., argentite, jalpaite and stromeyerite. Hence, the same three stages as described by Stillwell [14] from the Broken Hill Lode. The stromeyerite commonly shows the "oleander-leaf" structure (Fig. 100), similar to that described by Guild. Moreover, the entire specimen was coated with a thick crust of metallic silver. This metal did not replace the chalcocite as the other three sulphides did, but formed a true

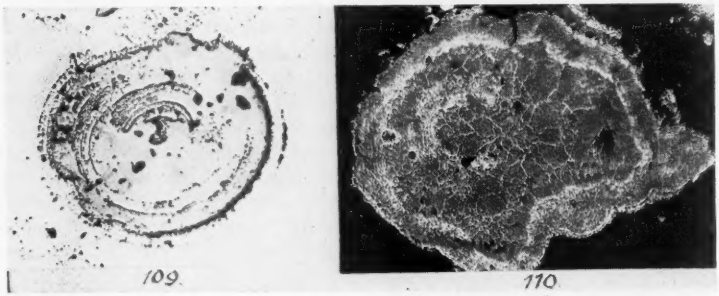

FIG. 109. Galena (almost white) with some jamesonite specks (faint gray) pseudomorphic after a globular FeS_2 concretion enclosed in pyrite (white). Could erroneously be considered contemporaneous gel-deposition. Some zones of pyrite remnants in the galena. Chocaya, Bolivia. × 35.

FIG. 110. Synthetic replacement of an original FeS_2 concretion (from Rammelsberg, Germany) by chalcocite (gray). Black, enclosing graywacke; white, pyrite remnants. Note the pyrite "dust," the concentric zones of fine pyrite remnants and the "veinlets" filled with pyrite. Such a structure can give the *wrong* conclusion of contemporaneous gel-deposition of pyrite and chalcocite and later filling of desiccation cracks with pyrite.

crustification. The four newly formed compounds indicate a considerable increase in volume. The following reaction might have occurred:

$$Cu_2S + 4\ AgNO_3 = Ag_2S + 2\ Ag + 2\ Cu\ (NO_3)_2.$$

This presents the following remarkable feature:

The silver solution on further attack must penetrate through the newly formed metasomes onto the replacement front in order to reach the underlying chalcocite. There the Cu-ions from the chalcocite must pass into solution and the Ag-ions are liberated and are partly precipitated in the Ag_2S-form in stromeyerite, jalpaite and argentite successively. As there is insufficient room at the replacement front for all of the silver that is set free, many of these Ag-ions must wander back through the newly formed compounds and cannot be precipitated until the polished surface is reached. There it forms a crustification of metallic silver.

[14] F. L. Stillwell, Austr. Inst. Min. Met., 1927, pp. 187–219.

Another, in some respects, comparable observation was made by replacement of gypsum by anglesite (Fig. 99). The specimen when sawed through showed from the inside outward: a kernel of unreplaced gypsum surrounded first by an open zone of vugs and then by a crust of anglesite with the crystal tops turned inward. Consequently, the lead solution reacts with the gypsum remnant in the center, the lead sulphate, however, was only precipitated on the tops of the formerly formed anglesite crystals at the other side of the vug. The final stage, after complete replacement of the gypsum, would be: a vug bordered by a zone of hypidiomorphic anglesite crystals forming a true crustification, seemingly grown on the original wall of the vug. Although it looks like a vug-filling, the process is mainly metasomatic with some loss of volume.

INSTITUTE OF TECHNOLOGY,
DELFT, HOLLAND, 1945,
March 15, 1946.

REVIEWS *

Geology and Ores of the Malånäs District, Västerbotten, Sweden. By SVEN GAVELIN. Sveriges Geologiska Undersökning. Ser. C., No. 424, Årsbok 33 (1939) No. 4. 1939. Pp. 198; Pls. 38. In English with Swedish summary.

The Malånäs district comprises a portion of the Skellefte region, centering about 45 km. WNW of the Boliden mine. This paper is a very detailed report on the geology and ore deposits of a district about 20 by 10 km. in area and represents at least 4 seasons of field work. It constitutes a unit of the detailed investigations that have been carried on by the Geological Survey of Sweden in this general area for many years.

The scope of the study is very thorough. It includes a general map of the area on a scale of 1:20,000 in which 14 cartographic units are distinguished, maps and sections through the half-dozen more promising sulfide deposits on a scale of 1:800, and many excellent photomicrographs of rocks and ores. Very detailed descriptions, both petrographic and mineragraphic have been made and a large number of volumetric analyses of thin sections, together with 9 rock analyses and many assay data, form the basis for the discussion. The results of extensive electrical and magnetic prospecting and considerable drilling have been utilized to extrapolate the geological observations.

The area is one of rather poor exposures, owing to the widely distributed glacial drift. This results naturally in a rather generalized map and considerable uncertainty as to many structural details. The geophysical data have been used in tying together the geology of the scattered exposures.

The principal rocks are of Archaean age: Metamorphosed volcanics including lavas and tuffs of quartz porphyry, quartz keratophyre, keratophyre and basaltic and andesitic greenstones, overlain by argillaceous and arenaceous meta-sediments. These rocks have been invaded by two granites: the older Jörn granite north of the mapped area and the younger Revsund to the south.

The supracrustal rocks have been overfolded to the north along westerly-trending axes. Fold axes pitch WSW in the eastern part of the area and are horizontal or pitch W at low angles in the western part. Toward the northern part of the area the metamorphic rocks have dominantly planar schistosity—in the terminology of Sander they are "S-tectonites"—toward the south the folding and rotation of the rocks have resulted in "B-tectonites." Gavelin points out that such sulphides as are known in the "S-tectonite" area are disseminated widely; massive ores are confined to the "B-tectonite" area and show definite control by the fold axes. He attributes this distinction to the more localized openings during the folding of the "B-tectonites" that served to guide the ore-bearing fluids, whereas the innumerable narrow S-surfaces of the "S-tectonites" led to the dissipation of the ore-fluids through much greater volumes of rock.

Gavelin recognizes regional metamorphic zoning related to the Revsund granite.

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, M. M. Leighton, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

The amphibole isograd in the basic rocks, which roughly coincides with the biotite isograd in the quartz-porphyries, passes near the center of the area. The transitional zone to the chlorite-calcite facies of the basic rocks is considerably narrower than the corresponding traditional zone to the chlorite facies of the quartz porphyries.

Two of the more important deposits of massive sulfides—Bjurträsk and Bjurliden—lie a considerable distance on the high grade side of the complete biotite amphibole isograd—two others—Eastern Bjurfors and Ö. Högkulla—lie in the transitional zone, the latter much nearer to the low-grade side. There are corresponding differences in the wall-rock alterations about the several deposits. At Bjurträsk, for example, the wall-rocks of the ore contain "fairly high-temperature parageneses" (gahnite, garnet, andalusite, cordierite, chloritoid, magnetite, staurolite, hornblende and intermediate to calcic plagioclase). At Bjurliden chloritoid is absent and calcite and epidote are more abundant; at Eastern Bjurfors, though the wall-rock alteration is considerable, the only Al, Fe, or Mg-enriched minerals are magnetite, chlorite, and sericite; at Ö. Högkulla, there is relatively slight alteration—chiefly of calcite-epidote and chlorite together, but locally garnet, magnetite and chloritoid also occur.

Immediately around the ore-bodies the rocks are highly silicified, and all feldspar has been destroyed—producing the "ore-quartzite" of Gavelin. Outside this zone is locally a zone of alternating anorthite-rich rocks and sericite-rich rocks. No change in bulk composition appears to have taken place in this zone, however, and Gavelin regards the occurrence as an example of metamorphic differentiation in the sense of Eskola, induced by the local ore solutions but receiving no material contribution from them.

Gavelin also believes that the massive ores of Bjurträsk and Bjurliden were formed chiefly by replacement, while those of Ö. Högkulla were chiefly open-space fillings. The Eastern Bjurfors deposit he regarded as probably intermediate, with "Replacement as well as displacement structures very distinct." (To the reviewer, Gavelin's criteria for disproof of replacement, see fig. 17, p. 126 and, "the occurrence of sharp contacts between compact ore and chlorite-quartzite, contacts which can be proved to be caused by fissure planes and thus do not represent a limit for a 'replacement front'" are not convincing.)

There are gradations from pure pyrite to pure pyrrhotite ores, and to either copper-rich or zinc-rich ores. There are few transitions between copper-rich and zinc-rich shoots. There are suggestions of differentiation within individual ore-bodies either late in their formation or due to remobilization of once-deposited minerals, leading to enrichment of the zinc shoots in lead, antimony and silver and of the copper shoots in copper. Arsenopyrite is found in small quantities and is auriferous as at Boliden. It seems to be enriched in the zinc-lead shoots, as compared to the copper shoots. Gavelin notes that this association is not in conformity with metal zoning as normally assumed. Furthermore, the different wall-rock alterations of the several deposits (indicating considerable temperature differences roughly conformable to the regional metamorphism) are not paralleled by any consistent differences in metal content. "A differentiation according to decreasing temperature and distance from a magma reservoir, as described e.g. by Emmons, is thus not applicable to the differentiation within the Malånäs District."

Gavelin has made very detailed polished-section studies and determined the following ore minerals: pyrite, pyrrhotite, arsenopyrite, chalcopyrite, cubanite, valleriite, bornite, covellite, sphalerite, stannite, galena, tetrahedrite, bournonite, jamesonite, boulangerite, geocronite, gudmundite, pyrargyrite, bismuth, electrum,

dyscrasite (?), copper, sulphur, marcasite, magnetite, hematite, ilmenite. Many excellent photomicrographs illustrate their relations.

This paper may be recommended to all geologists interested in ore deposits, petrology or metamorphism as a thorough, scholarly and significant contribution.

JAMES GILLULY.

English-French and French-English Technical Dictionary. By FRANCIS CUSSET. Pp. 590. Chemical Publishing Co., Brooklyn, N. Y., 1946. Price, $5.00.

This nicely printted volume is an up-to-date and accurate technical dictionary that covers geology, mining metallurgy, chemistry, electricity, mechanics and other sciences. It is prepared by a French engineer to assist engineers and other technical and scientific workers, as well as translators, librarians and students. It should be in every library and invaluable for students.

Principles of Field and Mining Geology. By J. D. FORRESTER. Pp. 645; figs. 316. John Wiley & Sons, N. Y., 1946. Price, $7.00.

This volume presents an analysis of geologic field techniques for the solution of geologic problems particularly relating to mining geology. It is meant primarily to acquaint students with field procedure but also for the use of practicing geologists. It is organized in four parts: I, Recognition of Geologic Phenomena; II, General Field Survey Practices and Procedures; III, Special Field Techniques of Mining Geology; IV, Interpretation and Use of Field Data. Throughout it emphasizes the process of recognizing and recording geologic phenomena, and the correlation, analysis and presentation of data. Particular attention is drawn to what is now generally considered to be an important source of future ore reserves namely, the study of old and abandoned mining camps, and studies of broad regional scope.

The chapter headings give an idea of the scope: 1, Rocks and Geologic Structures; 2, Field Criteria and Recognition of Geologic Structures; 3, Phenomena of Economic Mineral Deposits; 4, Correlation of Geologic Phenomena; 5, Field Equipment; 6, Survey Procedures; 7, Survey Methods and Instruments; 8, Surveying and Mapping Procedures; 9, Sampling; 10, Ownership and Mining Claim Locations; 11, Prospecting and Development Practices; 12, Library and Laboratory Research; 13, Maps, Illustrations, and Analysis; 14, Interpretations, Analyses, and Conclusions; Bibliography. The elements of geology are covered briefly in Chapters 1 and 2. Chapter 3 is a brief resumé of economic mineral deposits, 20 pages being devoted to non-metallic deposits, 24 pages to metallic deposits, and 35 pages to alterations, weathering, classification (this includes "true fissure veins," but untrue ones are not disclosed), and later of minerals and their distribution.

Part 2 (Chaps. 5–7) of 15 pages is a very excellent summary of field methods, equipment, instruments and surveying tables. Part 3 (Chaps. 8–11) of 112 pages contains some good rules for underground mapping with useful colored illustrations; a chapter on sampling is handy as are also sections on mining statutes and a compilation of development methods and procedures. In Part 4 are many practical tips on mapping and sectioning illustrated by some good large-scale parts of maps of structures and deposits. Considerable space is devoted to ore reserves, their computation and valuation which evidently embodies much of the author's personal experiences.

The book is profusely illustrated; the drawings are excellent, but many of the photos are just small insets, a number of which are too small to be intelligible.

The book should prove to be a valuable one for practicing field geologists and parts of it will serve usefully for text purposes.

Our "Vanishing" Natural Resources—a Symposium. Pp. 39. Nat. Res. Dept., 34th Ann. Meeting, U. S. Chamber of Commerce, Washington, D. C., 1946.

This is a round table discussion held at Atlantic City in May, 1946. It includes the following articles: Introduction, by Ralph S. Carr, chairman; The States' Interest in Natural Resources, by Robt. S. Kerr; The Coal Industries, by M. L. Patton; The Petroleum and Gas Industries, by W. B. Heroy; The Water and Power Industries, by N. E. Funk; The Forest Products Industries, by Chas. A. Gillett; The Mining Industries, by W. C. Broadgate; The National Picture, by Evan Just; Discussion. This is a group of papers by men whose industry, government, or political associations permit interesting viewpoints.

BOOKS RECEIVED.

General Outline of South American Oil Fields. VICTOR OPPENHEIM. Pp. 35; map. Pan Amer. Inst. Min. & Geol., Tech. Paper No. 4, 1946. *Brief resumé by countries of oil fields, beds, structures, production and reserves.*

Exploration of Oil and Gas in Western Kansas in 1945. W. A. VER WIEBE. Pp. 112; map. Univ. of Kan. Pub., State Geol. Surv. Kan., Bull. 62, 1946. *Resumé by countries of drilling, status of pools, and production.*

Geological Institute of Poland, Warsaw, 1939 (released 1946).

Bull. 10. Structure geologique des Karpates dans la Région de Dynów. JAN WDOWIARZ. Pp. 24, fig. 1; maps 3. (Polish and French.) *Cretaceous to Oligocene stratigraphy; structure.*

Bull. 15. Travaux geologiques (1938) dans le Massif de St. Croix, en Volhynie et en Polesie. Pp. 120; figs. 20; maps 9. (Polish, English and French.) *Structure stratigraphy, structure and magnetic prospecting.*

Bull. 17. Contributions a la geologie de la Pologne (in 1938–39). Pp. 30. (Polish and French.) *Miscellaneous geological notes.*

Bull. 18. Activité de l'Institut Géologique de Pologne en 1938. Director KAROL BOHDANOWICZ. Pp. 140; maps. (Polish.) *Summary of field reports.*

Bull. 20. Champs de Gaz de Sadkowa-Roztoki-Sobniów. H. SWIDZINSKI. Pp. 11; maps 10. (Polish.) *Resumé of gas fields.*

Bull. 21. Petrographic Investigations of Boghead coal, Radzionkow mine, Upper Silesia. ADAM DRATH. Pp. 82; figs. 6, plates 15. (Polish and English.) *Descriptions and origin; excellent photomicrographs.*

Review of Petroleum Geology in 1945. F. M. TUYL, W. S. LEVINGS AND OTHERS. Pp. 203; maps. Quart. Colo. School of Mines, Vol. 41, No. 3. Golden, Colo., 1946. Price, $2.00. *This annual review, as before, covers important new developments in geologic and allied sciences as related to petroleum geology. It also covers aerial photographs, world exploration and development, production and reserves, trends in petroleum geology, future of the oil industry and has 58 pages of bibliography.*

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Mineral Resources of Ohio. WILBER STOUT. Pp. 33. Geol. Surv. of Ohio, 4th Ser., Inf. Circ. No. 1. Columbus, 1946. *Brief resumé of mineral resources, mostly non-metallic.*

Efforts Tangentiels et Efforts Verticaux dans la Tectogenèse. P. FOURMARIER. Pp. 106; figs. 11. Annal. Soc. Geol. de Belgique V. 69. Liège, Belgium, 1946. *The first part deals with a critical examination of facts of observation and the second part with an hypothesis of tectogeny, including geosynclinial and folding phases, and rift valleys.*

Zum Zinnkiesproblem. PAUL RAMDOHR. Pp. 30; figs. 17. Pruss. Acad. der Wassen., Jahr. 1944. Berlin, 1944 (released 1946). *Complex tin ores and their origin.*

Geologic Map of Illinois. Compiled by J. M. Weller. Scale 1: 500,000; size 48 × 60 in.; colors. *Gives present and preglacial topography, structure, inconformities, overlaps.*

Les Gisements de Terres Plastiques et Réfractaires d'Andenne et du Condroz. LÉON CALEMBERT. Pp. 204; figs. 50. H. Vaillant-Carmanne, Imp. de L'Acad. Liège, 1945 (1946). *Detailed locality descriptions of plastic and refractory clays; their origin and practical conclusions.*

Comité Spécial du Katanga. Ann. Ser. d. Mines, Vol. 10, 1945. Contribution à l'Etude du Système du Lubudi. FL. SCHELLINICK. Pp. 83; pls. 5. Brussels, 1946. Detailed stratigraphy and petrography of sediments and metamorphic rocks.

Who's Who in America, Vol. 24, 1946–1947, 50th Anniversary Number. Pp. 2815. A. N. Marquis Co., Chicago, 1946. Price, $11.80. *A new, revised and enlarged edition of this well-known volume.*

Scientific Instruments. HERBERT J. COOPER. Pp. 305; illust. Chemical Publishing Co., Brooklyn, N. Y., 1946. Price, $6.00. *Comprehensive coverage of optical, measuring, navigational and surveying, liquid testing, and miscellaneous instruments, for professional and non-professional readers and users.*

Well Sample Records. J. H. C. MARTENS. Pp. 889. West Virginia Geol. Surv., vol. 17, Charleston, W. Va., 1945 (1946). *Samples, laboratory methods, terms, stratigraphic boundaries and detailed records.*

Hollidaysburg-Huntingdon Folio, Pennsylvania. CHARLES BUTTS. Pp. 20; columnar section; topo. map, 20-ft. contours; areal and structure maps in colors; pls. 27. U. S. Geol. Surv. Folio 227. Washington, D. C., 1945 (1946). *Excellent work on a folded area.*

Cuadernos de Mineralogie y Geologia, Vol. 4, No. 15. Pp. 72. Tucuman, 1946.

Permian Phosphate Deposits of Montana, Idaho, Wyoming and Utah. P. S. CLABAUGH. Scale 1:1,000,000. Stratigraphic mineral investigation preliminary map 3–198. U. S. Geological Survey. Washington, D. C., 1946. *A map 20 x 34 inches showing in red an outline of outcrops of phosphate deposits and and in dotted lines probable deposits.*

SCIENTIFIC NOTES AND NEWS

A mid-year meeting of the American Association of Petroleum Geologists at Biloxi, Mississippi on October 24 and 25 is to be devoted to the presentation of papers discussing the stratigraphy and geology of southeastern United States and the geology of typical oil fields in the area.

ARTHUR B. CLEAVES has recently been appointed Associate Professor of Geology in the Department of Geology and Geological Engineering at Washington University in St. Louis.

REGINALD S. DEAN, former assistant director of the U. S. Bureau of Mines, has set up his office and laboratory as a metallurgical engineer and consultant specializing in electro-metallurgy and alloys at 2041 K Street, N. W., Washington, D. C.

CHALMER L. COOPER, formerly geologist with the Illinois State Geological Survey, has been appointed senior geologist with the U. S. Geological Survey, Washington, D. C., where he is coordinating the activities of the various Branches in the preparation of Survey reports for publication.

COLONEL JAMES BOYD has been appointed dean of the faculty of the Colorado School of Mines effective September 1. Recently he has been directing industrial operations in the American zone of German occupation as a deputy to Lieutenant General Lucius D. Clay and has been awarded the Oak Leaf Cluster to the Legion of Merit award. During the war Colonel Boyd was chief of the metals office in the office of the undersecretary of war and directed production control for supervisory headquarters of the allied expeditionary forces and for the forces of the United States in the European theater.

DR. LAURENCE L. SLOSS, associate professor of geology, has accepted an appointment as lecturer in paleontology at Northwestern University and has resigned from the Montana School of Mines.

ARTHUR BEVAN, state geologist of Virginia, has been appointed chairman of the Division of Geology and Geography of the National Research Council for the three year term from July 1, 1946. He succeeds William W. Rubey of the U. S. Geological Survey, whose term had expired.

GEORGE F. HANSON has been appointed instructor in geology at Union College to assist Prof. Edward S. C. Smith.

GEORGE R. BANCROFT of Vancouver, B. C., has been appointed consulting geologist for Rusdon Gold Mines, Ltd.

FRANK A. AYER, consulting engineer for the Copper Range Co., has been elected a vice-president of the Company.

The Mapua Institute of Technology, Manila, P. I., lost all of its buildings during the liberation of Manila, including its collection of rocks and minerals. They desire donations of extra specimens of rocks and minerals and will pay for the cost of packing and transportation when a bill is rendered. We should all try to help the Institute.

The 2nd Pan American Congress of Mining and Geology to be held at Rio October 1–15 has found it necessary to transfer headquarters from Rio to the excellent facilities at Petropolis because of congested hotel conditions at Rio.

THOMAS MITCHAM is working as geologist for the Ground Hog mine of the American Smelting and Refining Co. at Vanadium, New Mexico.

RICHARD M. FOOSE resigned on September 1 as senior geologist of the Pennsylvania Geological Survey to become professor of geology and head of the department of geology at Franklin and Marshall College, Lancaster, Pennsylvania.

CLAY T. SMITH recently transferred from the Union Mines Development Corp. to the geological department of the Union Carbide and Carbon Corp. as a field geologist assigned to the Winnemucca unit of the U. S. Vanadium Corp.

PARKER D. TRASK has resigned from the University of Wisconsin and is back with the U. S. Geological Survey in Washington, D. C.

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